Rockslides on limestone cliffs with sub-horizontal bedding in the southwestern calcareous area, China

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Abstract: Calcareous mountainous areas are highly prone to geohazards, and rockslides play an important role in cliff retreat. This study presents three examples of failures of limestone cliffs with sub-horizontal bedding in the southwestern calcareous area of China. Field observations and numerical modeling of Yudong Escarpment, Zengzi Cliff, and Wangxia Cliff showed that pre-existing vertical joints passing through thick limestone and the alternation of competent and incompetent layers are the most significant features for rockslides. A "hard on soft" cliff made of hard rocks superimposed of soft rocks is prone to rock slump, characterized by shearing through the underlying weak strata along a curved surface and backward tilting. When a slope contains weak interlayers rather than a soft basal layers, a rock collapse could occur from the compression fracture and tensile split of the rock mass near the interfaces. A rock slide might shear through a hard rock mass if no discontinuities are exposed in the cliff slope, and sliding may occur along a moderately inclined rupture plane. The "toe breakout" mechanism mainly depends on the strength

characteristics of the rock mass.

Key words: cliff failure; sub-horizontal bedding; plane slide; toe splitting; rock slump; numerical modeling

1. Introduction

The southwestern calcareous area of China covers a large area of 54.4 × 10^3 km^2, and it is highly prone to geohazards. Many multilayered carbonate rocks with sub-horizontal bedding have been deeply cut by rivers during crustal uplift and form significant topographic relief in steep slopes and cliffs. These sub-horizontal cliff slopes are usually dominated by two sets of sub-vertical conjugate joints and are characterized by slightly folded or faulted to massive rock masses. Rockslides from sub-horizontally bedded cliff failure and resulting catastrophes have occurred widely and frequently in the southwestern calcareous area of China.

Considerable research on cliff failure has been conducted in similar areas around the world(Abele, 1994; Von, 2002; Rohn, 2004; Embleton, 2007; Ruff, et al., 2008; Palma, et al., 2012), such as the North Calcareous Alps in Austria. It is believed that water, lithology, geological structure, and karstification are of primary importance in triggering rockslides from cliff failure (Kay, et al., 2006). These factors dominate the tearing and shearing failure mechanism of the rock masses and joints, which are directly displayed in the consequent failure behavior of the cliff slopes. Types of rockslides with different detachment mechanisms (slumps, plane slides, topples, and lateral spreading) in sub-horizontally bedded cliffs with particular geological settings and triggering mechanisms have been described by engineering geologists, e.g., the collapse of the Mt. Sandling and Mt. Raschberg limestone towers had a complex failure sequence from lateral spread to toppling followed by rock fall (Rohn, et al., 2004). In addition to lateral spreading, a cliff slope with a geological formation of hard rock on a soft base may undergo the translational sliding or slumping of slab-shaped blocks (Poisel, 2005). In addition, the karst process is an inevitable factor in rockslide formation. Tectonic joints keep widening and extending to the deep of rock mass by constant dissolution and disgregation of underground water, forming boundaries of perilous rocks (Santo, et al., 2007). It is believe that karst plays an important role in rockslides from carbonate mountains, especially for gently bedding-inclined slopes which are unfavorable to failure.

Active underground mining is widespread in the southwestern calcareous area of China. There is the potential for damage to cliff faces and overhangs when mining activity occurs beneath cliffs. This has been repeatedly shown to be true. Taking the Southern Coalfields of Australia as an example, several types of cliff failure have been witnessed in the goaf area, although no instabilities have been reported beyond the mining area (Kay, 2006). However, there is no available and widely accepted model that can predict the failure susceptibility of steep slopes close to mining. This is because of the complex interaction of factors influencing the stability of steep slopes, which include geometry, geology, geological structure, environmental factors, and technical mining parameters. An integrated method combining landslide science and mining subsidence science is promising as a direction for future research.

This study focuses on the failure mechanisms of cliffs with sub-horizontal bedding in the southwestern calcareous area of China and the recognition of these features in field investigations. The three cases presented occurred during the last 10 years and caused great damage to both human life and assets. Furthermore, post-failure behavior, such as rock avalanches and debris flows, is not included in descriptions of failure mechanisms of steep slopes. The term “failure mechanism” in this study particularly refers to the detachment mechanism of rock masses from the cliff slope.

2. Geological background

The likelihood of rockslide instability in the southwestern calcareous China is high, mainly because of the local geological evolution. Tectonic movement during the Mesozoic was characterized by compression and formed the area into a fold belt, mainly striking NNE. Neotectonic uplift raised the thick carbonate rocks to high altitude and shaped the steep and folded landforms.

Many layers of carbonate rocks were deposited from Permian until Triassic time, and were interbedded with weak planes or soft strata. The carbonate rock masses possess great strength and integrity; thus, they usually form steep slopes hundreds of meters high, e.g., the Three Gorges, if there are no intercalated soft strata. Under these circumstances, slope movement is mainly controlled by discontinuities such as weak interlayers, karst, and fissures. The thick carbonate succession in the southwestern calcareous area of China contains multiple layers of weak shale planes, including carbonaceous shale and pyrobituminousshale. The strength of the shale planes is relatively low and significantly varies with the weathering process, from virgin rock to fractured planes to argillated layers. The strength of carbonaceous shales sandwiched in the Lower Permian limestone at Lianziya Cliff is low that the cohesion and internal friction angle are 0.08–0.39 MPa, 18°–21° and 0.06–0.078 MPa, 18°–19.8° for dry and saturated samples, respectively (Ding, et al. 1990). The weak interlayers play a significant role in mass movement. When soft strata underlie hard rock, the yielding of the soft base may cause the uneven subsidence of the cap rock. Lateral spreading and slumps with backward tilting are caused by this type of destabilization mechanism, in which failure propagates uphill.

In the southwestern calcareous area of China, coal measures are common soft strata, accompanied by thick carbonate sequences. Except for coal seams, the coal measures are usually composed of associated interlayers of shale, carbonaceous shale, pyrobituminousshale, and bauxitic claystone. Mining is active in these coal measures using the techniques of room and pillar mining and longwall mining. The depth of cover ranges from dozens to hundreds of meters. It is believed that underground mining activities can change the engineering geological conditions and reduce the stability of cliffs (Tang, 2009; Altun, et al., 2010; Marschalko, et al., 2012; Lollino, et al., 2013）, . Cliff failures and the resulting catastrophes, examples of which are discussed below, are related to underground mining.

Karstification is a significant factor when discussing the reasons for carbonate slope failure. It particularly affects steeply inclined faults and tectonic joints and slowly widens the discontinuities to create large open fractures, which foster rockslides (Santo el al., 2007; Parise, 2008). In addition, the karstification process can cause a significant reduction in the mechanical properties of the carbonate rock mass. This is very important for toe-constrained slides, which depend on the strength of the rock mass at the toe. In some cases, the underground karst voids play the same role as goaf, and cavern breakdown may also lead to landslides (White, et al., 1969; Parise, 2010).

3. Failure mode

Different types of rockslides have been observed in thickly and sub-horizontally bedded limestone escarpments. Gently inclined bedding is unfavorable for large translational slides. Slide, collapse, and slump slope failures are discussed below in detail to explain their mechanisms. Three examples are given: the Yudong Escarpment, Zengzi Cliff, and Wangxia Cliff (Fig. 1).

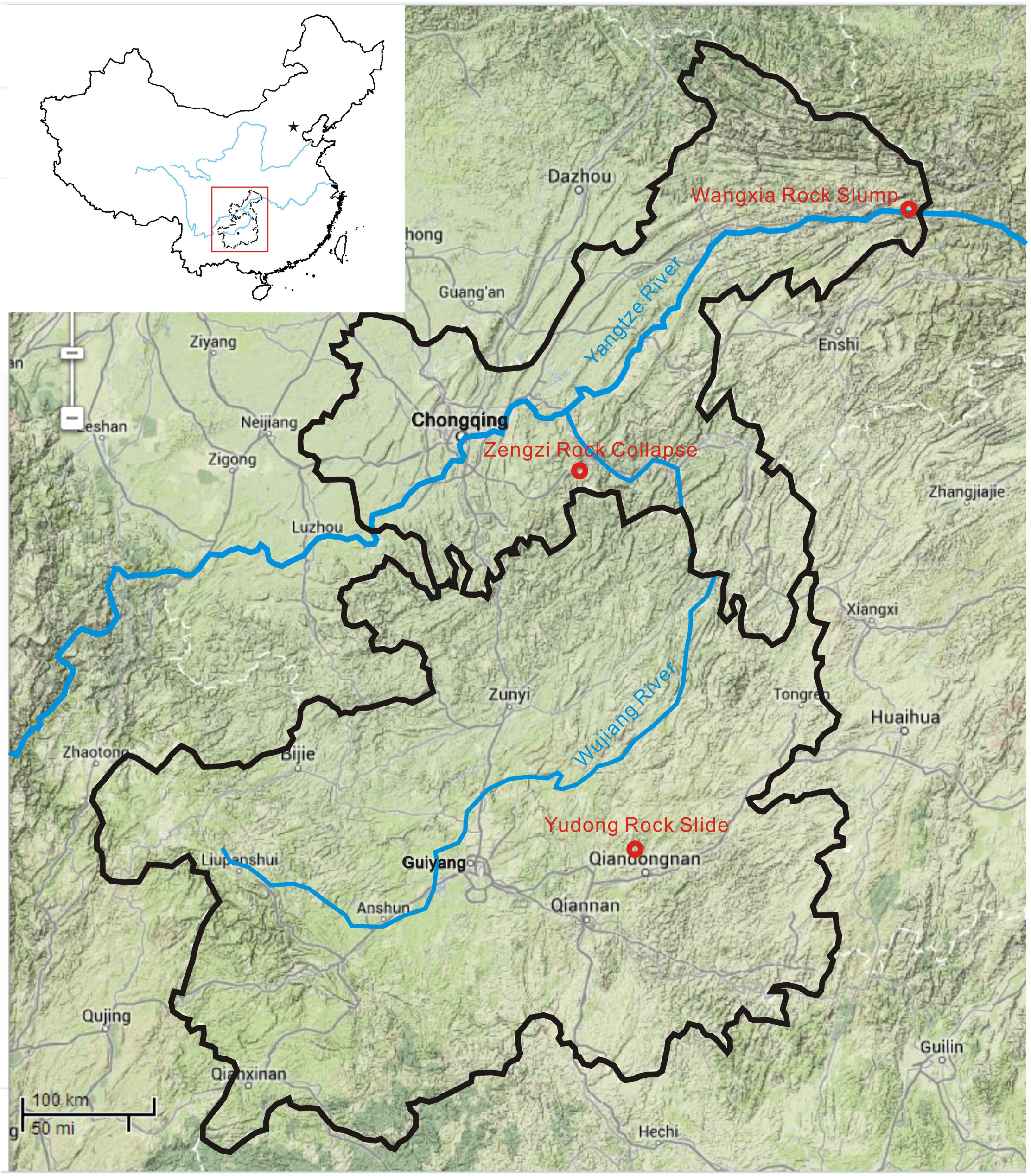


Fig. 1 Locations of three rockslides: Wangxia Rock Slump, Zengzi Rock Collapse, and Yudong Rock Slide.

(1) Rock slide at the Yudong Escarpment

On February 18, 2013, a rock slide occurred in Longchang County, Guizhou Province. The mass movement is located in a high and steep bank of the Yudong River, close to an underground mining area (Fig. 2). The S308 provincial road runs on the opposite bank of the river. The rock slide buried several houses and five people beneath the escarpment and blocked the river.

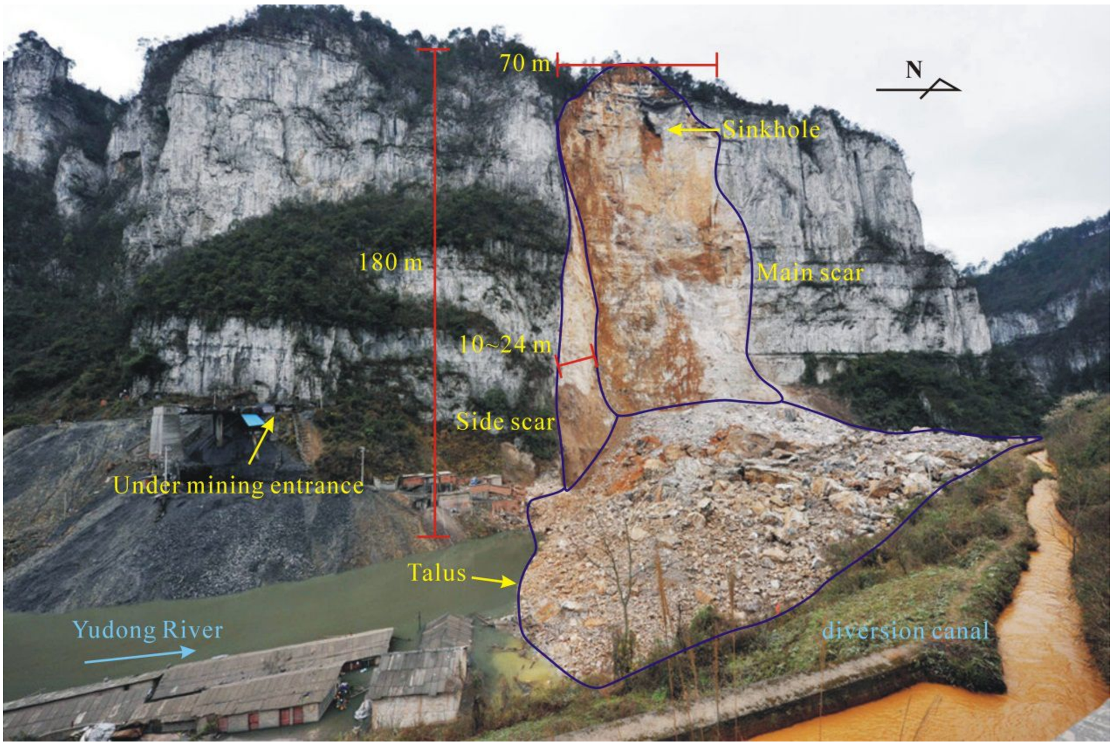
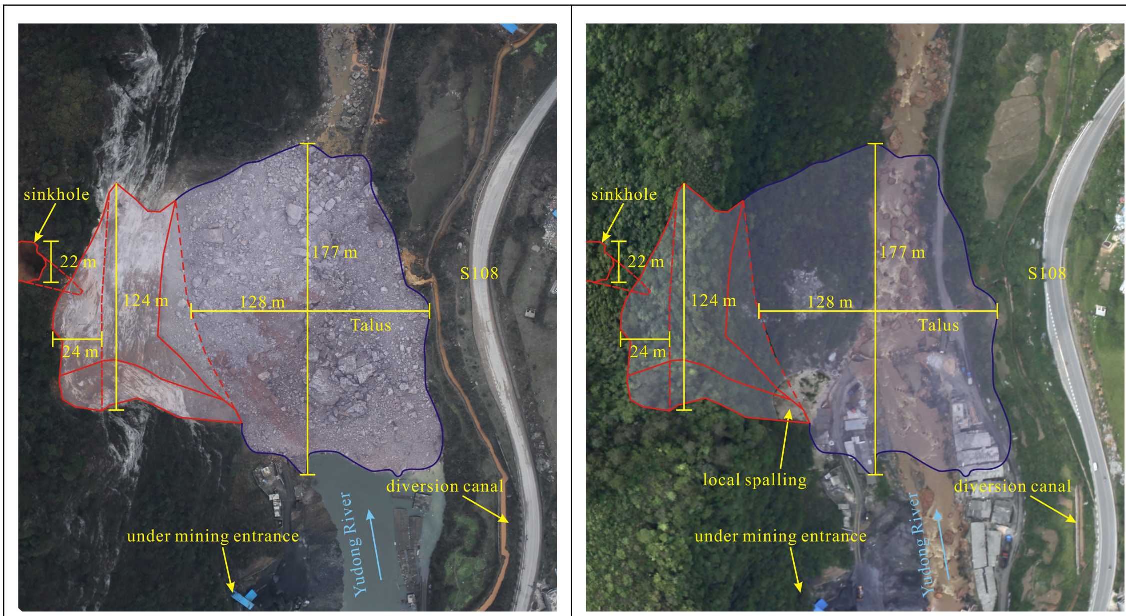


Fig. 2 Photograph showing an overview of Yudong rock slide I.

The Yudong Escarpment is about 220 m high and the slope angle is more than 80°. The steep slope faces in the direction ~~SE~~100°–130°, and the dip direction is ~~NW~~325°, with slightly inclined bedding. The outcrop consists of thickly bedded P_1^2 limestone and underlying P_1^1 coal measures. The jointed limestone is moderately weathered, and the uniaxial compression strength of intact rock reaches 30 MPa. The coal measures are composed of thickly bedded argillaceous shale and coal seams. Coal extraction has been active in the soft basal unit, and the goaf is about 200 m deep behind the cliff face. The Yudong Escarpment lies in the gentle eastern flank of the Yudong Syncline, which strikes NNE. As a result, a set of NNE-trending joints and a conjugate set of

NW-trending joints are present in the rock mass. The orthogonal 130°∠70° and 80°∠75° joints cut the 325°∠9° rock beds into prism- and tower-shaped blocks on the edge of the cliff. The “2.18” Yudong rock slide originates from one of these unstable blocks with a volume of about 30×10^4 m^3. Several types of karst are observed in the rock slide area, including sinkholes, karst tunnels, and dissolution fissures. A remote sensing image taken the day after the rock collapse shows a sinkhole at the crest with a diameter of 2.2 m immediately behind the fall. The pipe flow and induced groundwater dynamics acted on the unstable rock block and changed the instability. However, because of abundant vegetation, the sinkhole is not visible in a previous image that was taken in the summer of 2012 (Fig. 3). The intense karstic erosion of a yellowish-orange color has been observed on the vertical scar. The selective karst widens and connects the pre-existing steep joints so that the area of the rock bridge covers less than 30% of the main scar (Huang, 2013). The directed scratches indicate the brittle failure of the rock bridges and consequent fall of the rock mass. The rock slide left two scars originate from joints. The main scar is nearly parallel to the cliff face and about 80 m wide. The upper part of the main scar is a sub-vertical plane, and the lower parts are planar and dip out of the cliff. The conjugate side scar is about 24 m wide and perpendicular to the cliff face (Fig.2).



a   b

Fig. 3 Aerial photos of Rock Slide Itaken in summer 2012 (a) and on February 19 2013 (b). The zoning of the depleted mass and talus is projected in picture (a) prior to the catastrophe. The abundant vegetation and steep terrain make it difficult to distinguish the potential failure. However, there were signs of local spalling at the toe of the cliff face (a). A 22-m-diameter sinkhole was exposed in winter, which connected with the main back scar of the rock slide (b).

Another massive rock slide (II) (Fig. 4) occurred on April 16, 2013, about 100 m away from the February 18 rock slide (I). The morphology of the vertical scar of rock slide II is similar to that of rock slide I. The lower rupture surface forms a steep and irregular scar (Fig. 5). These two rock slides have the same failure mechanism of a steep back scar separating the unstable block from the escarpment and the block breaking through the toe leading to free fall of the rock mass. The rupture surface implies a plane slide involving shear failure through the rock mass. There is little or no shear displacement along the rupture surface, and the velocity is very high. The brittle failure of the rock mass in the toe area can be explained by the brittle failure of the rock mass under uniaxial compression tests. In other words, it is largely dependent on the mechanical properties of the rock mass at the toe. The toe is sheared along random discontinuities of limited persistence traced by the rupture surface (Fig. 6).

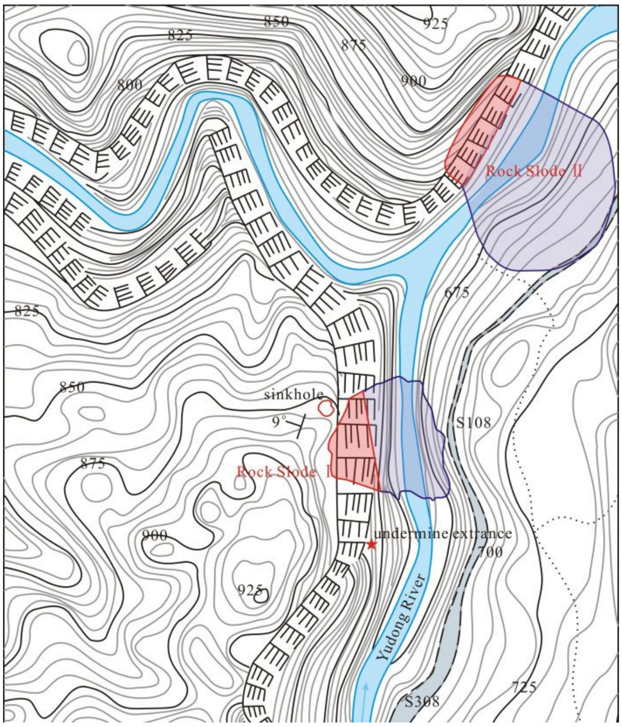


Fig. 4 Rock slide II is located north of rock slide I and has the same geological conditions, except for undermining. The volume of the talus of rock slide II is 30×10^4 m^3. It blocked the Yudong River and covered 80 m of the S308 road.

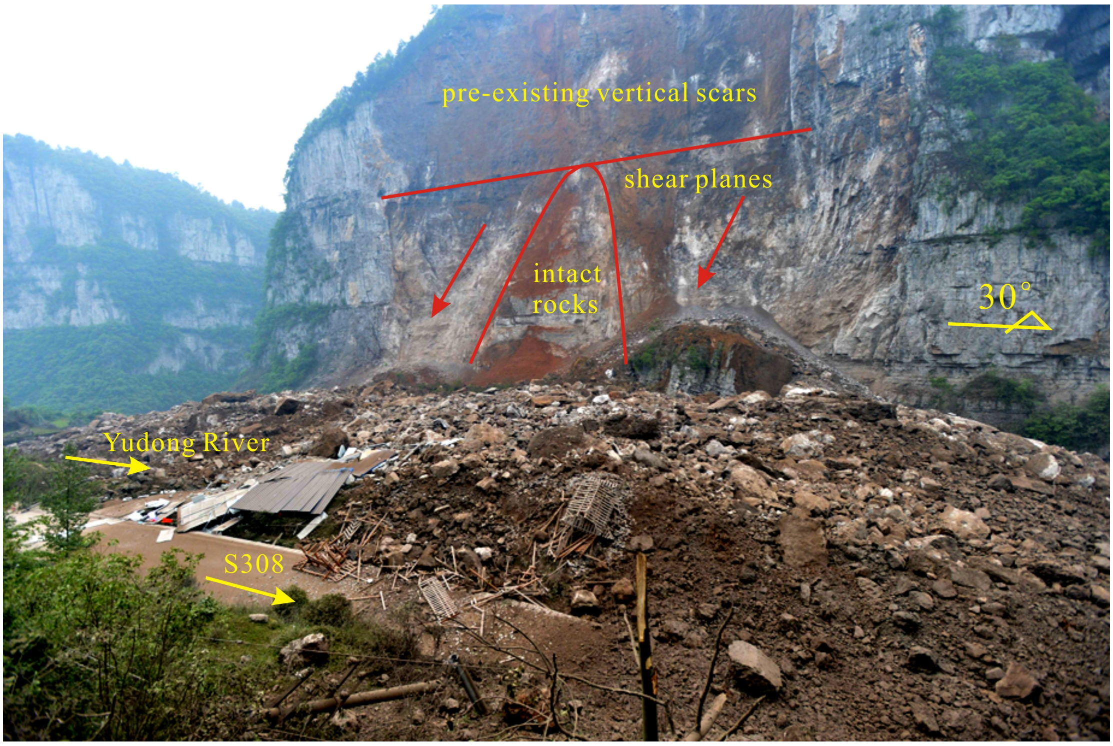


Fig. 5 Photograph showing rock slide II at Yudong. The pre-existing vertical scars are coated with karst of a yellowish-brown color, while the rupture surfaces are white and gray, indicating brittle failure and planar sliding through the limestone.

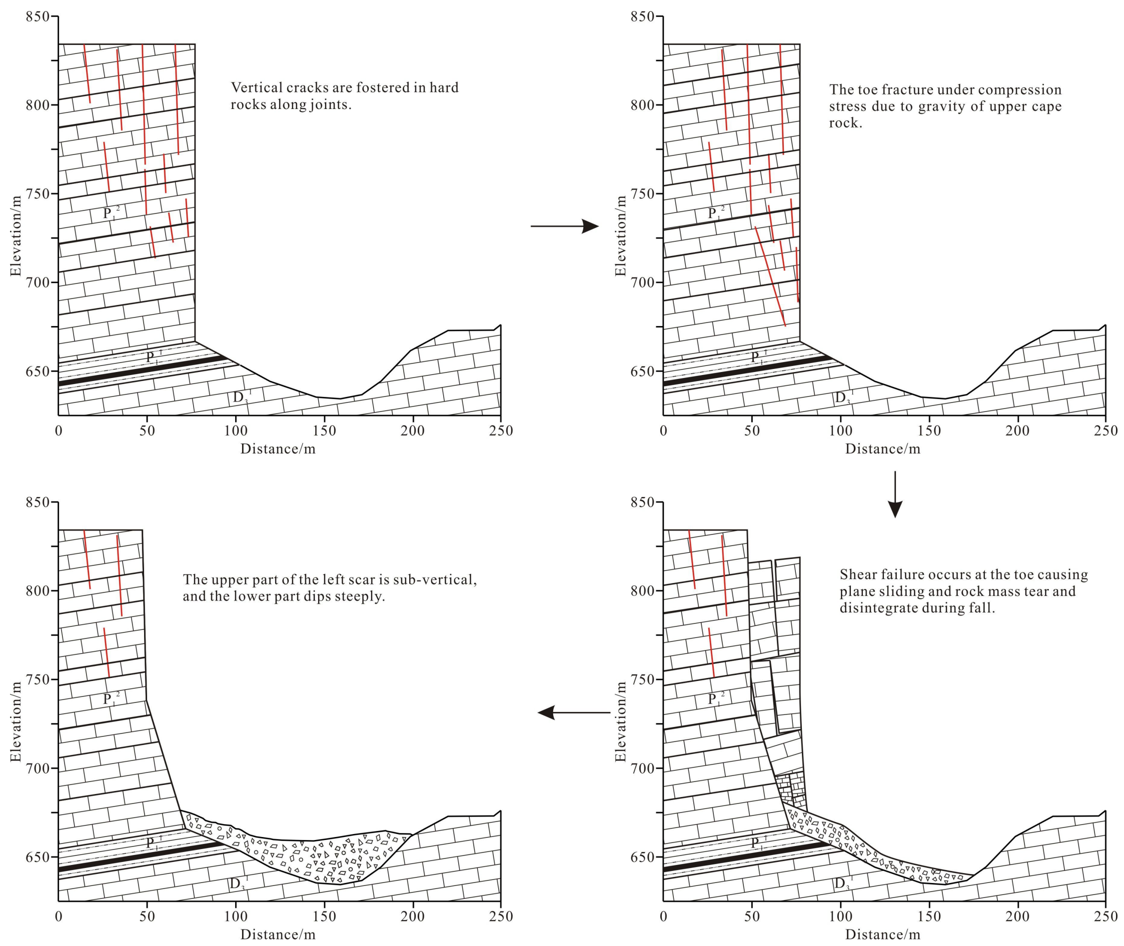


Fig. 6 The evolutionary process of toe shear and planar sliding of the Yudong rockslides.

(2) Rock collapse at Zengzi Cliff

Zengzi Cliff lies in the gentle and wide core of the Jinfo Mountain Syncline, Nanchuan County of Chongqing, in a “hard on soft” landform. The vertical limestone consists of two platforms separated by softer rock (Fig. 7). Two major tectonic joints in the hard rocks strike at N40°–50°E and N30°–50°W, with dip angles of 70°–88°. These two sets of joints are approximately orthogonal to each other and perpendicular to bedding. The bedding trends at 300°–305° with a very low inclination (4°–7°). The upper platform is U in shape; hence, the steep slope varies from anaclinal to plagioclinal and cataclinal in different parts of the edge. Beneath the cliff, S_1 silty shale forms a soft base and a gentle slope (20°–30°). Talus occurs everywhere under the cliffs, indicating that cliff failure occurs as scarp retreat.

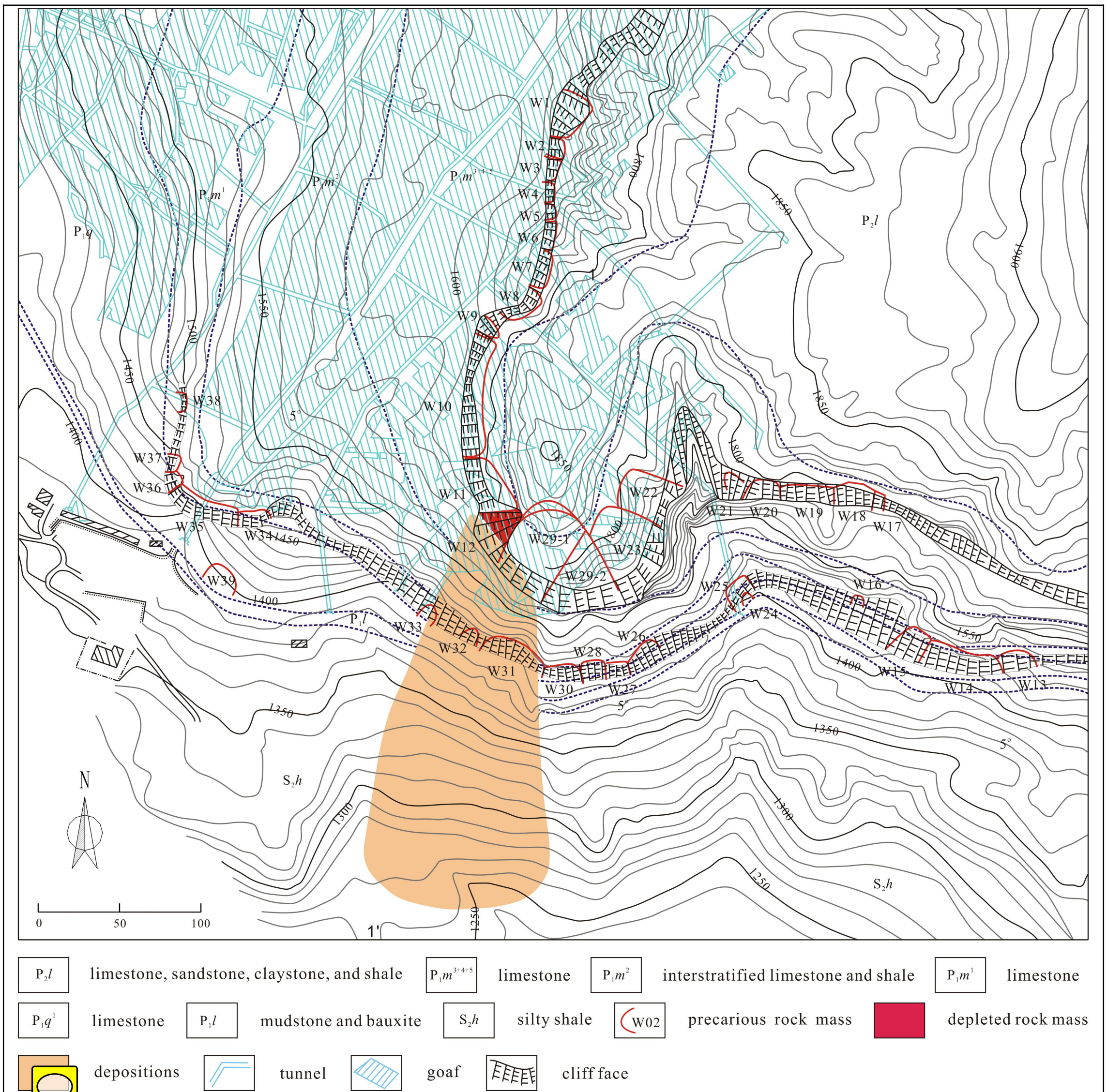
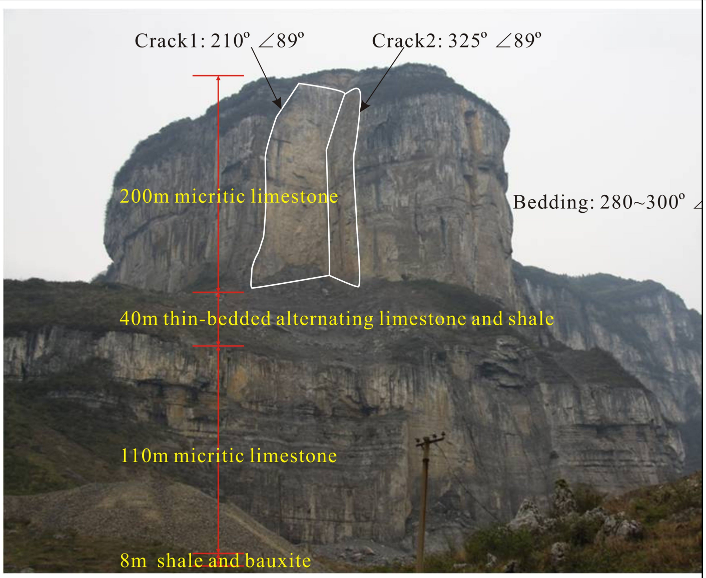


Fig. 7 Topographic map of the Zengzi Cliff area and the distribution of precarious rock masses on its edge. Room and pillar mining has been conducted in the P_1l sequence since 1983, and the goaf extends from south to north. The depth of the goaf is about 100–120 m for the first step and 350–400 m for the second step.

Rocks frequently fall in the Zengzi Cliff area. On August 12, 2004, a massive rock collapse occurred in the upper platform, which is about 200 m high (Fig. 8). The depleted mass is a prism block shaped by sub-vertical joints and bedding. Two vertical back scars and a groove surface in the underlain soft strata are exposed after the collapse. Large areas of the scars are coated with karst argillaceous fillings and yellowish-orange calcite, while the rock bridge failure scars are fresh. Field investigations showed that the head scars are wide open prior to the massive collapse. Seepage forces and frost from percolating water acted on the prism block over a long time and influenced the stability; however, only karst could alter the conditions in the rock adjoining the slope by increasing the connectivity of back scars. The underlying soft strata consist of alternating beds of thin-bedded shale and medium-bedded limestone, and as a result of weathering, form a 40-m-high slope.



a. Elevation view of Zengzi Cliff

b. Side view of the rock collapse

Fig. 8 a. Alternating strata of hard rocks and weak rocks; b. Cracks (red lines) originated near the interface between the hard cap and weak base and propagated uphill.

Mining activity has been conducted for decades, but community monitoring started in 2001. The opening velocity of the head scar was very slow from 2001 to 2003 (Ren, 2005). It increased to 4–15 mm/10 d in the period between April and July 2004 (Fig. 9), and signs of pre-collapse, (rock falls) were repeatedly observed. At that time, the government issued warnings and evacuated residents and workers. The velocity abruptly increased from August 10, and the increment reached 658 mm on the last day. The process of the Zengzi rock collapse was captured on video: the tower dropped vertically and disintegrated while falling. It is unusual that the failure initiated in the bottom of the hard block rather than the underlying soft strata. The splitting of the hard rock mass at the toe led to tower collapse. The curved surface in the soft strata will have been carved by collision.

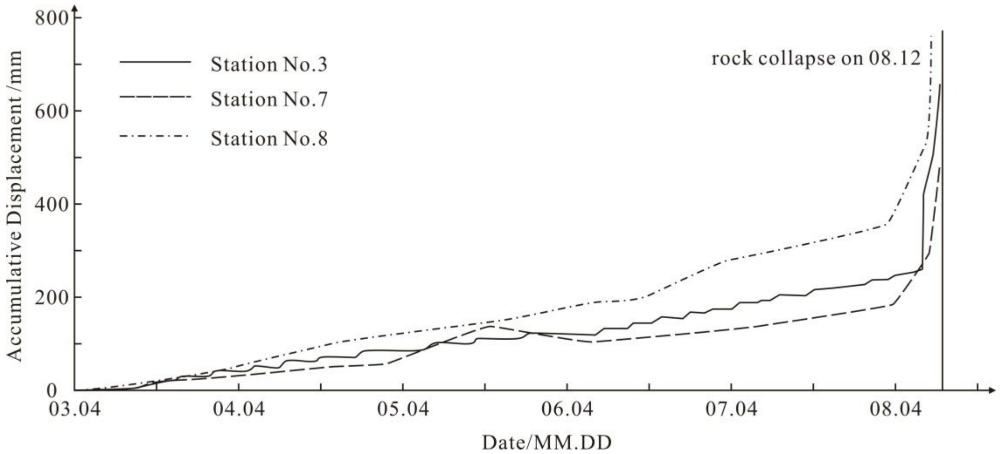


Fig. 9 Cumulative displacement of monitoring stations at the crest of Zengzi Cliff in 2004 (Ren, 2005).

Tensile splitting has been observed in uniaxial compression tests of rock samples with high brittleness and strength, such as limestone. There are several reasons why the collapse did not start with shear failure in the underlying strata. The rock mass in the bottom of the tower block is in poor condition: fractured and weathered. Drill cores obtained strongly karstic rock containing dissolution pores, caves, tufa, and calcite. The drilling also revealed at least 11 fissures, some of which were filled with yellow clay (107 Geology Team, 1995). This is because the underlying strata are low-permeability soft rocks; hence, there are steady water flows immediately above.

Furthermore, the soft strata are not sufficiently weak. These strata consist of interbedded thin layers of shale (0.1–0.2 m) and medium-thick limestone. The tower block could easily shear through the shale but not the intercalated limestone. Under these circumstances, tensile split failure of the tower bottom is a reasonable failure mechanism, involving compression fracturing and horizontal shearing in the shale beds (Fig. 10). Field studies and deformability tests on rock masses all around the world have demonstrated that folded and flat-lying rock masses are prone to tensile splitting near thin weak planes. Compression fracturing and tensile splitting are important failure mechanisms for sub-horizontally bedded slopes. The Zengzi cliff collapse exposed back scars in the nearby deformable rock mass, which propagated uphill (Fig. 8b), and a fractured rock mass was observed near the shale interface.

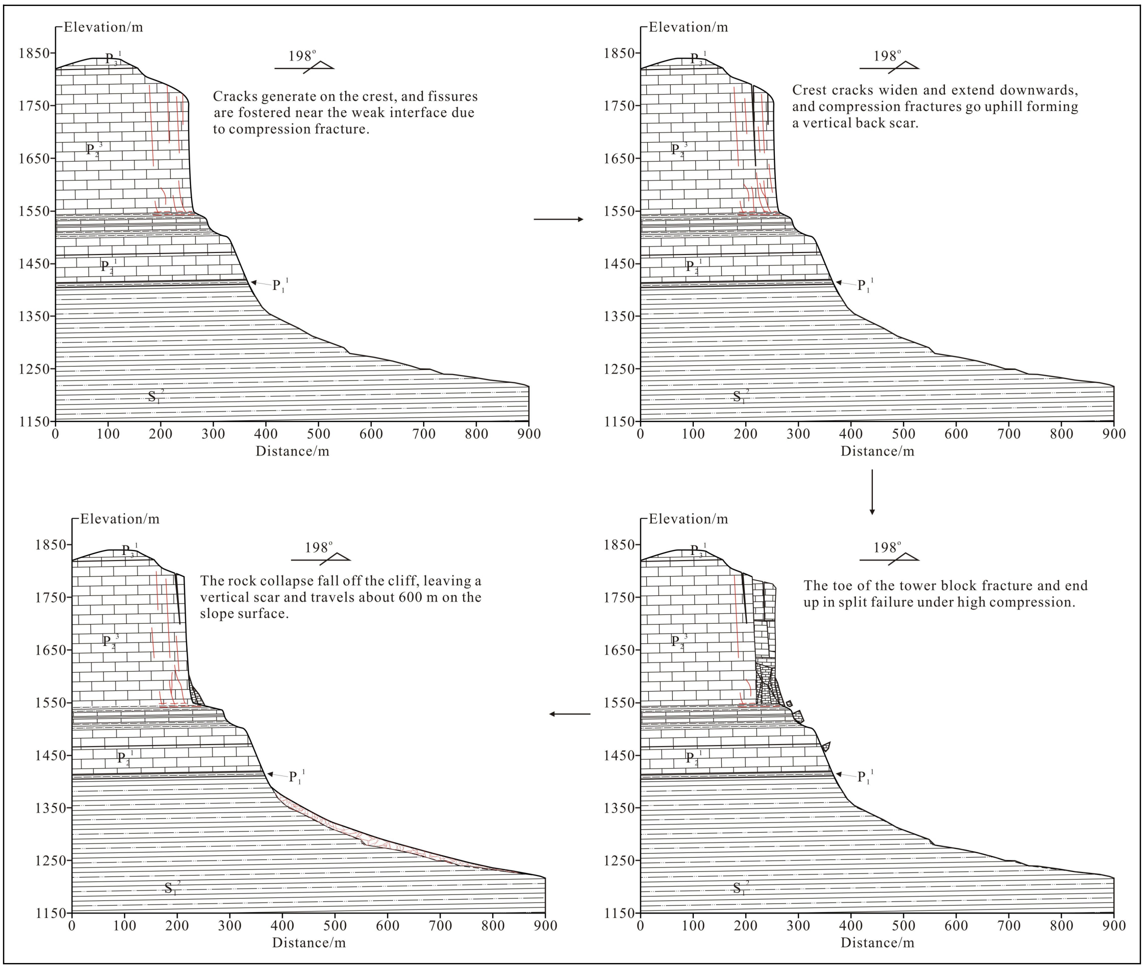


Fig. 10 Failure process of the Zengzi rock collapse, involving toe splitting and tensile failure.

(3) Rock slump at Wangxia Cliff

When the base is sufficiently weak, and there is a steep fracture separating the column from the slope in the cap area, a rock slump with back-tilting mechanism is likely to occur. The Wangxia Cliff failure slump mechanism involved isolated limestone block breaking through shale at the toe, with rotational movement. The Wangxia Cliff is situated at the top of the right bank of the Yangtze River in Wushan County of Chongqing, about 1000 m above the water level (Fig. 11). Located in the flat core of the Hengshixi Fold, the bedding is slightly inclined (3°–8°) and strikes at 335°–340°, opposite to the cliff face. Interbedded shales, mudstones, and coal seams form a gentle slope and separate the Upper Permian limestone into two cliff steps. A country road passes over the slope below the 70–75-m high limestone escarpment, which contains several isolated slab- and prism-shaped blocks. On October 21, 2010, a prism with a volume of 7×10^4 m^3 became a rock slump failure.

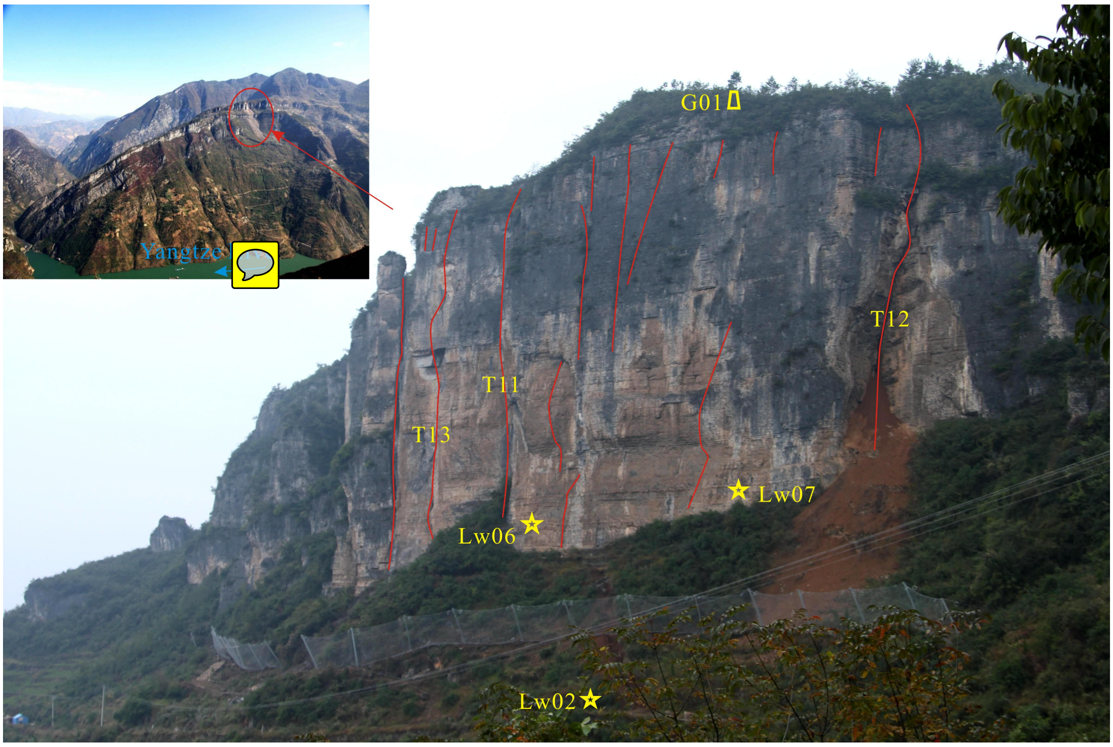


Fig. 11 Overview of Wangxia Cliff prior to the catastrophic rock slump. G01 represents a GPS station, and Lw02–Lw07 indicate the displacement monitoring stations. The rock slump of October 21, 2010 was controlled by vertical scars T11 and T12. The red lines represent fissures in the rock mass.

The slope movement can be traced back to June 18, 1999. Four collapsecraters and nine cracks were observed in the crest area after 108.5 mm of rainfall on June 15 and 16 (Le, et al., 2011). Intensive deformation began on August 21, 2010, after four days of concentrated rainfall. Repeated pre-collapse signs were observed. Crown cracks widened, and new cracks occurred on the crest. Rocks fell off from the cliff face and vertical scars in the rock mass. In addition, gravelly soils flowed out from steep cracks at the toe. Transverse ridges and cracks were observed on the country road beneath. The mass movement accelerated as a result of 70 mm of precipitation from October 10 to 13. The fissures in the isolated blocks extended and widened. Rock falls became more obvious both in volume and frequency. Finally, a massive rock slump occurred on October 21, in which the isolated prism slid downhill, breaking through the toe and leaning against the back scars. The underlying weak rocks were squeezed out and scattered over the slope surface. Displacement monitoring showed that the crest was dominated by subsidence, while the horizontal and vertical displacements were about the same at the base. The incompetent base showed horizontal movement and little subsidence. These phenomena were caused by ductile yielding and rotational shearing in the incompetent base (Fig. 13). The squeezing out contributed to the uphill propagation of cracks and disintegration of the mountain into slab- and prism-like blocks.

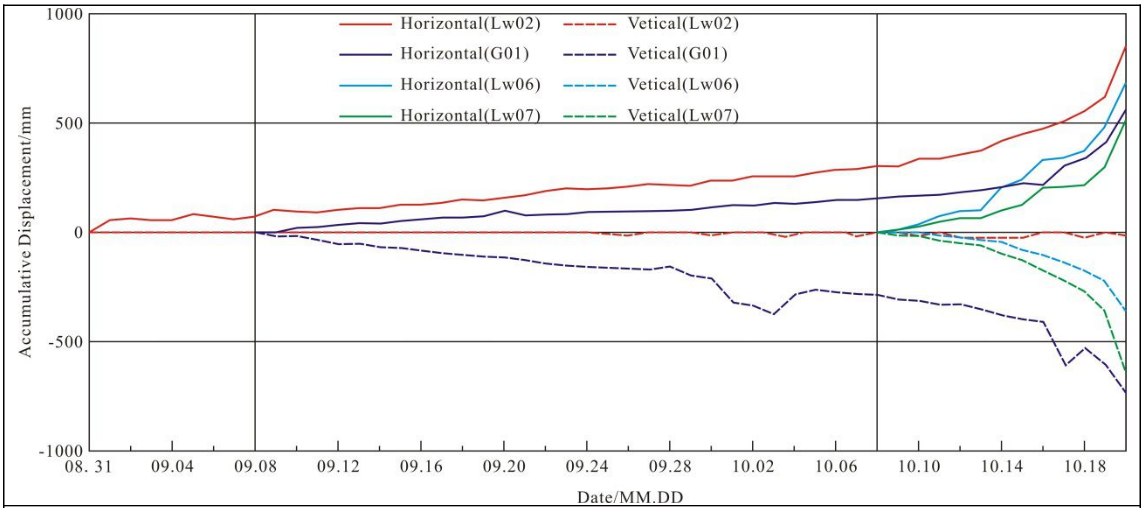


Fig. 12 Cumulative displacement at monitoring stations at the Wangxia rock slump (Le, et al., 2011).

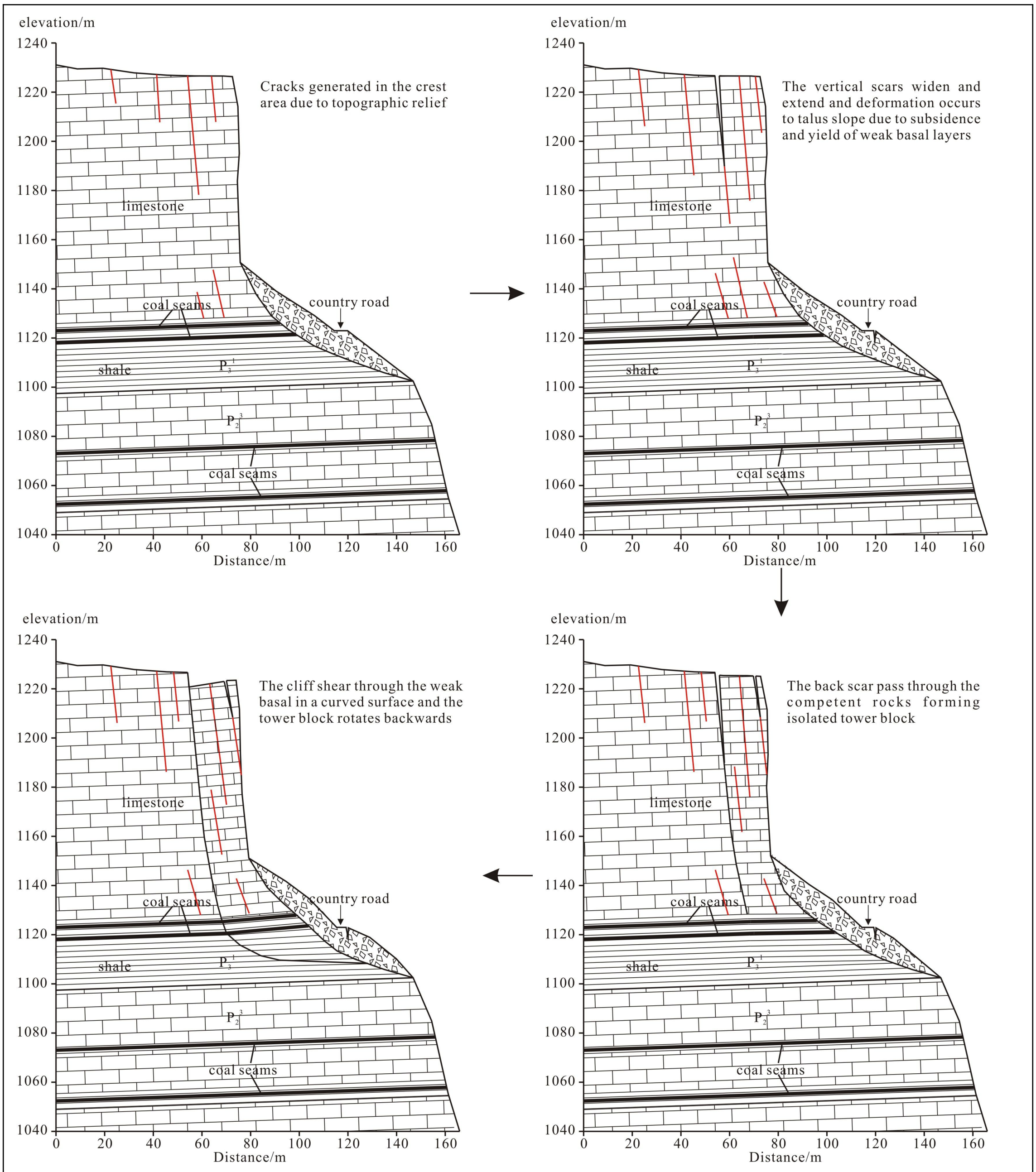


Fig. 13 Deformation and failure processes of the Wangxia rock slump.

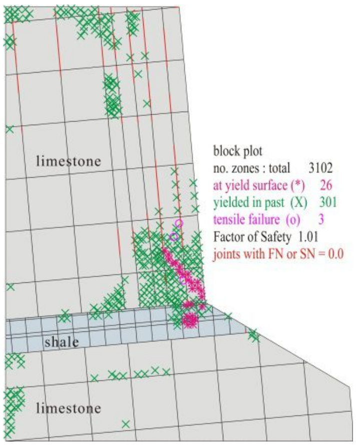
It is worth mentioning that there is a good correlation between the acceleration of displacement and concentrated rainfall. Because of cracks and fissures in the limestone, water could easily and rapidly percolate into the weak strata. The unconfined compressive strength (UCS) of the shale shows a substantial decrease when saturated, and the softening factor is about 0.62. However, there is a 2–4 day time lag between concentrated rainfall and acceleration of displacement, because the infiltration of water into poorly permeable shale takes time.

4. Numerical back-analysis

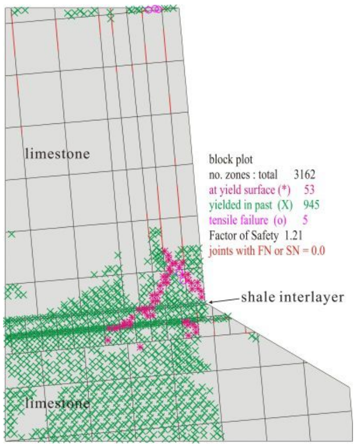
Numerical analysis is a sophisticated method for assessing the potential failure modes of rock slopes. We use it herein to validate the cases discussed above, which show different failure mechanisms for sub-horizontally bedded cliffs (compound slide, rock collapse, and rock slump) and to explain the backgrounds to the slides. The computation was performed using the computer program UDEC; the parameters used in the simulation are given in Table 1.

Table 1 Parameters used in the numerical simulation

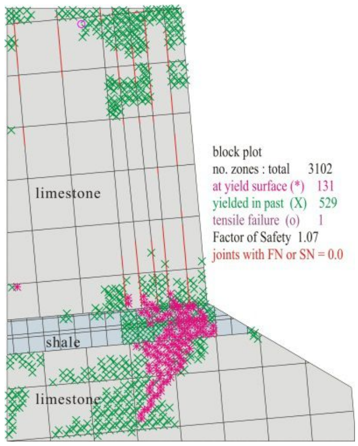
parameter	limestone	shale		
		Rock slide	Rock collapse	Rock slump
Thickness (m)	170	20	2	20
Density(kg/m^3)	2700	2640		
Young's modulus, E(GPa)	65	5		
Poisson'sratio	0.13	0.2		
Friction angle of rock mass (°)	32	28	20	25
Cohesion of rock mass (MPa)	1.3	0.8	0.4	0.5
Tensile strength of rock mass (MPa)	0.3	0.1	0.04	0.04
Friction angle of joints (°)	30	25		
Cohesion of joints (MPa)	1.0	1		
FOS	-	1.01	1.21	1.07



a. Toe shearing and plane sliding.

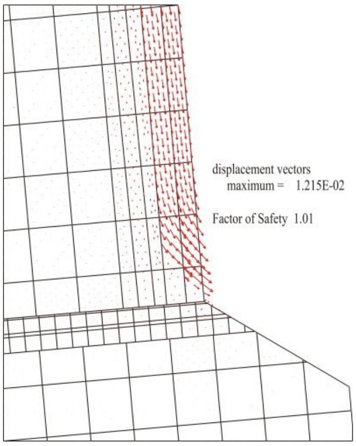


b. Toe splitting and collapse.

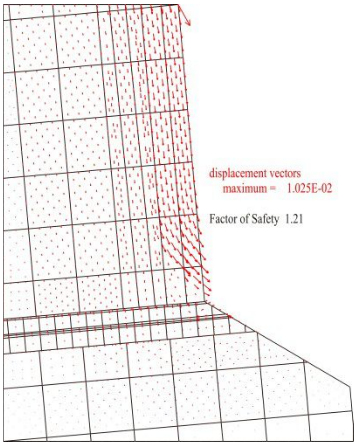


c. Rotational shearing and slumping.

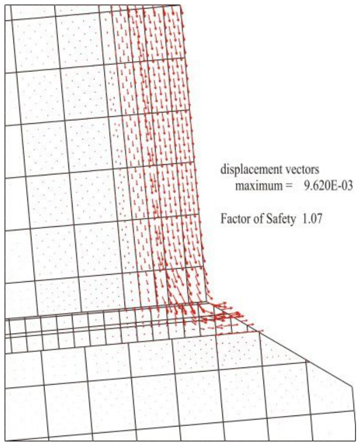
Fig. 14 Plastic state and joint opening for rockslide initiation in cliff slopes.



a. Toe shear and plane slide.



b. Toe splitting and collapse.



c. Rotational shear and slump.

Fig. 15 Displacement vectors of the initial failures of cliff slopes.

The natural stress field is characterized by a tensile zone on the crest and stress concentration at the toe. When a thick incompetent basal layers is present, the jointed slope tends to fail as a slump. A yielding curved surface gradually emerges in the basal layers under long-term gravitational compression of the upper cap rock. A large plastic zone is present in the weak basal layers and nearby hard rock mass (Fig. 14c). The horizontal movement of the weak stratum is prominent.

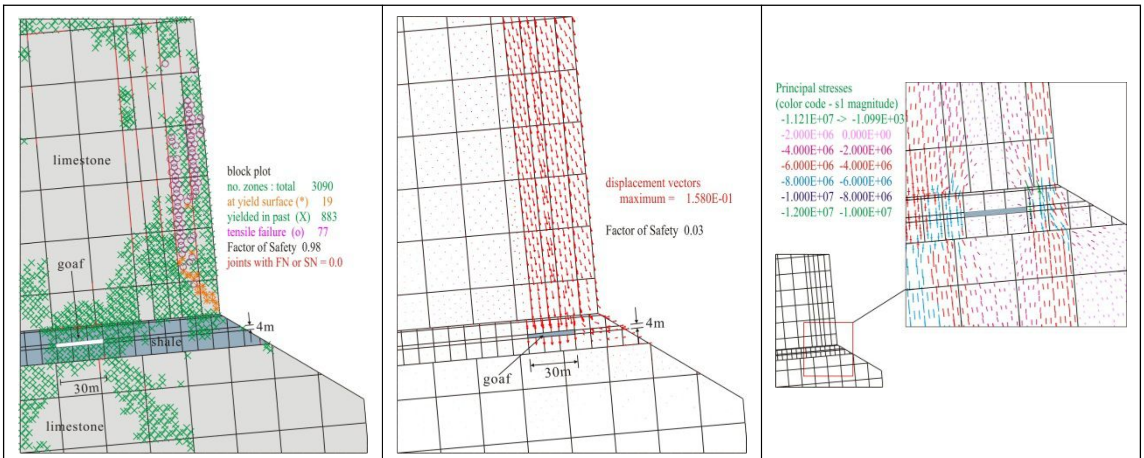
Pre-existing joints in the hard rock mass widen upward and slip with the ductile flow of the basal layers. The movement of the massive unstable rock mass is dominated by subsidence in the crest area and back tilting at the toe (Fig. 15c).

When the weak basal is a thin interlayer, rotational slide through the toe is unlikely to occur. The horizontal shear stress determines the possibility of shear failure in the beds. For a sub-horizontal bedded slope with gentle tectonic disturbance during geologic evolution, the horizontal to vertical stress ratio is generally less than 1 (Zhang, et al., 1994). This indicates that it is possible for a weak interlayer with a frictional angle less than 45° to shear horizontally. Under these circumstances, the plastic zone ranges over the interlayer as well as the overlying competent rocks. The rock mass at the toe is in a plastic state as a result of compression fractures. Two yield surfaces dipping in opposite directions are formed (Fig. 14b), similar to tensile failure behavior for some brittle rock samples. The displacement prior to collapse is limited, and remarkable squeezing out is unlikely to be observed in the toe area (Fig. 15b).

A rock slide might burst out in hard rock where back scars cut through, and no discontinuities or weak strata are exposed at the toe. Irregular scars caused by brittle and shear failure through rock mass dip out of the cliff faces. The yield zone is mainly located at the block toe but not in the underlying rocks(Fig. 14a). The fracture of the toe rock mass gives rise to joints opening immediately above. Numerical computation gives a plane yield surface at the bottom of the separated block, which is called a potential failure surface (Fig. 15a). A small displacement appears before the outbreak of a compound slide. However, ground fractures on the crest and spalling in the toe area might occur.

5. Underground mining

The failures at the three locations described above are related to large areas of mining out. Pells (2008) used a continuum 2D model to assess macro-scale movements of cliff faces caused by total extraction and proved that the steep slope tends to tilt outwards when mining occurs beneath the cliff, and extraction well behind the cliff face causes back tilt. Our similar simulations are shown in Fig. 16. The rock slide model in Fig. 14a was adopted. The roof tends to collapse, and the surrounding rocks gradually fracture. The undermining-induced subsidence of the crest causes the dilation and tensile failure of the rock mass (Fig. 16a). The FOS decreases from 1.01 to 0.98 when the underground mining is located behind the cliff face. When the extraction is directly beneath the cliff, the rock mass is subjected to a small constraint; hence, cliff failure break-out through the fractured rock mass between the goaf and open face is feasible (Fig. 16b). The maximum principal stress on both sides of the goaf increases while that of the overlying rocks decreases (Fig. 16c).



a. Plastic state and joint opening slope failure when mining occurs behind the cliff.	b. Displacement vector of slope failure when mining occurs beneath the cliff.	c. Principal stress of slope failure when mining occurs beneath the cliff.

Fig. 16 Numerical simulations of mining in cliff slopes.

6. Conclusions

In this study, three different examples of failure in sub-horizontally bedded limestone cliffs are discussed. The failures are characterized by pre-existed vertical joints passing through thick limestone. The Yudong rock slide originated in a limestone cliff edge and left a moderately inclined rupture plane, implying shear failure through the hard rock. Rock collapse caused by compression fracture and tensile splitting of the rock mass near the interface between the hard cap and weak stratum occurred at Zengzi Cliff. The Wangxia cliff failure showed a slow rock slump sheared through the underlying incompetent rock mass along a curved surface. The mechanism of toe breaking mainly depends on the strength characteristics of the rock mass.

Considering that the rock mass near the cliff face is not laterally constrained, it is reasonable to assume that the there is a massive UCS failure at the toe of the vertical tower and slab blocks. Some failure characteristics of jointed rock mass in in situ UCS tests have been observed all around the world, for both shear and tensile failure. Of special concern is tensile failure in horizontally bedded rock masses with interlayers. Compression fractures emerge near the interfaces and form vertical slabs, which eventually split. Another possibility is squeezing out of weak interlayers as a result of compression fracture, causing the hard rock nearby to yield to tensile stress and disintegrate. It is worth noting that the UCS of the rock mass in compression fracturing is much lower than that of intact rock. A criterion based on horizontal shear failure along weak interlayers and the UCS ratio of the cap and underlying rock masses could be used to assess the failure mode of tower and slab blocks on cliff edges.

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