1 **Rockslides on limestone cliffs with sub-horizontal bedding in the southwestern calcareous**

2 **area, China**

3

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10

11 **Abstract:** Calcareous mountainous areas are highly prone to geohazards, and rockslides play an

12 important role in cliff retreat. This study presents three examples of failures of limestone cliffs

13 with sub-horizontal bedding in the southwestern calcareous area of China. Field observations and

14 numerical modeling of Yudong Escarpment, Zengzi Cliff, and Wangxia Cliff showed that

15 pre-existing vertical joints passing through thick limestone and the alternation of competent and

16 incompetent layers are the most significant features for rockslides. A "hard on soft" cliff made of

17 hard rocks superimposed of soft rocks is prone to rock slump, characterized by shearing through

18 the underlying weak strata along a curved surface and backward tilting. When a slope contains

19 weak interlayers rather than a soft basal, a rock collapse could occur from the compression

20 fracture and tensile split of the rock mass near the interfaces. A rock slide might shear through a

21 hard rock mass if no discontinuities are exposed in the cliff slope, and sliding may occur along a

22 moderately inclined rupture plane. The "toe breakout" mechanism mainly depends on the strength

批注 [I1]: The "layers" is deleted

23   characteristics of the rock mass.

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

25   modeling

26

27   **1.   Introduction**

28   The southwestern calcareous area of China covers a large area of 54.4×10^3 km^2, and it is highly

29   prone to geohazards. Many multilayered carbonate rocks with sub-horizontal bedding have been

30   deeply cut by rivers during crustal uplift and form significant topographic relief in steep slopes

31   and cliffs. These sub-horizontal cliff slopes are usually dominated by two sets of sub-vertical

32   conjugate joints and are characterized by slightly folded or faulted to massive rock masses.

33   Rockslides from sub-horizontally bedded cliff failure and resulting catastrophes have occurred

34   widely and frequently in the southwestern calcareous area of China.

35   Considerable research on cliff failure has been conducted in similar areas around the world(Abele,

36   1994; Von, 2002; Rohn, 2004; Embleton, 2007; Ruff, et al., 2008; Palma, et al., 2012), such as the

37   North Calcareous Alps in Austria. It is believed that water, lithology, geological structure, and

38   karstification are of primary importance in triggering rockslides from cliff failure (Kay, et al.,

39   2006). These factors dominate the tearing and shearing failure mechanism of the rock masses and

40   joints, which are directly displayed in the consequent failure behavior of the cliff slopes. Types of

41   rockslides with different detachment mechanisms (slumps, plane slides, topples, and lateral

42   spreading) in sub-horizontally bedded cliffs with particular geological settings and triggering

43   mechanisms have been described by engineering geologists, e.g., the collapse of the Mt. Sandling

44   and Mt. Raschberg limestone towers had a complex failure sequence from lateral spread to

45 toppling followed by rock fall (Rohn, et al., 2004). In addition to lateral spreading, a cliff slope

46 with a geological formation of hard rock on a soft base may undergo the translational sliding or

47 slumping of slab-shaped blocks (Poisel, 2005). In addition, the karst process is an inevitable factor

48 in rockslide formation. Tectonic joints keep widening and extending to the deep of rock mass by

49 constant dissolution and disgregation of underground water, forming boundaries of perilous rocks

50 (Santo, et al., 2007). It is believe that karst plays an important role in rockslides from carbonate

51 mountains, especially for gently bedding-inclined slopes which are unfavorable to failure.

52 Active underground mining is widespread in the southwestern calcareous area of China. There is

53 the potential for damage to cliff faces and overhangs when mining activity occurs beneath cliffs.

54 This has been repeatedly shown to be true. Taking the Southern Coalfields of Australia as an

55 example, several types of cliff failure have been witnessed in the goaf area, although no

56 instabilities have been reported beyond the mining area (Kay, 2006). However, there is no

57 available and widely accepted model that can predict the failure susceptibility of steep slopes close

58 to mining. This is because of the complex interaction of factors influencing the stability of steep

59 slopes, which include geometry, geology, geological structure, environmental factors, and

60 technical mining parameters. An integrated method combining landslide science and mining

61 subsidence science is promising as a direction for future research.

62 This study focuses on the failure mechanisms of cliffs with sub-horizontal bedding in the

63 southwestern calcareous area of China and the recognition of these features in field investigations.

64 The three cases presented occurred during the last 10 years and caused great damage to both

65 human life and assets. Furthermore, post-failure behavior, such as rock avalanches and debris

66 flows, is not included in descriptions of failure mechanisms of steep slopes. The term "failure

67 mechanism" in this study particularly refers to the detachment mechanism of rock masses from the

68 cliff slope.

69

70 **2. Geological background**

71 According to the Geo-hazards Survey Plan lunched by Ministry of Land and Resources of China

72 since 1999, most of the counties and cities in the southwestern calcareous China are most serious

73 area suffering from geo-hazards (Zhang et al, 2000; Li et al, 2004). The likelihood of rockslide

74 instability in the area is high, mainly because of the local geological evolution. Tectonic

75 movement during the Mesozoic was characterized by compression and formed the area into a fold

76 belt, mainly striking NNE (Fig.1). Neotectonic uplift raised the thick carbonate rocks to high

77 altitude and shaped the steep and folded landforms.

批注 [S2]: Q: The influence of karst and softer layer were discussed well, but the title of this section is geological background, so I suggest that add a column lithology map about the detailed P & T time, including the hard rock and soft interbed. The reviwer will make it clear that why the soft and karst are very important.
A: A rock sequence is added and listed in Figure 2. Orders of the figures is revised. And the lithology is also described in line 76-90 and are introduced respectively in each case. In addition, stratigraphic profiles in section 3 showed the interbedded limestone and weak shale.

批注 [I3]: Q: more detailed information about the region is need.
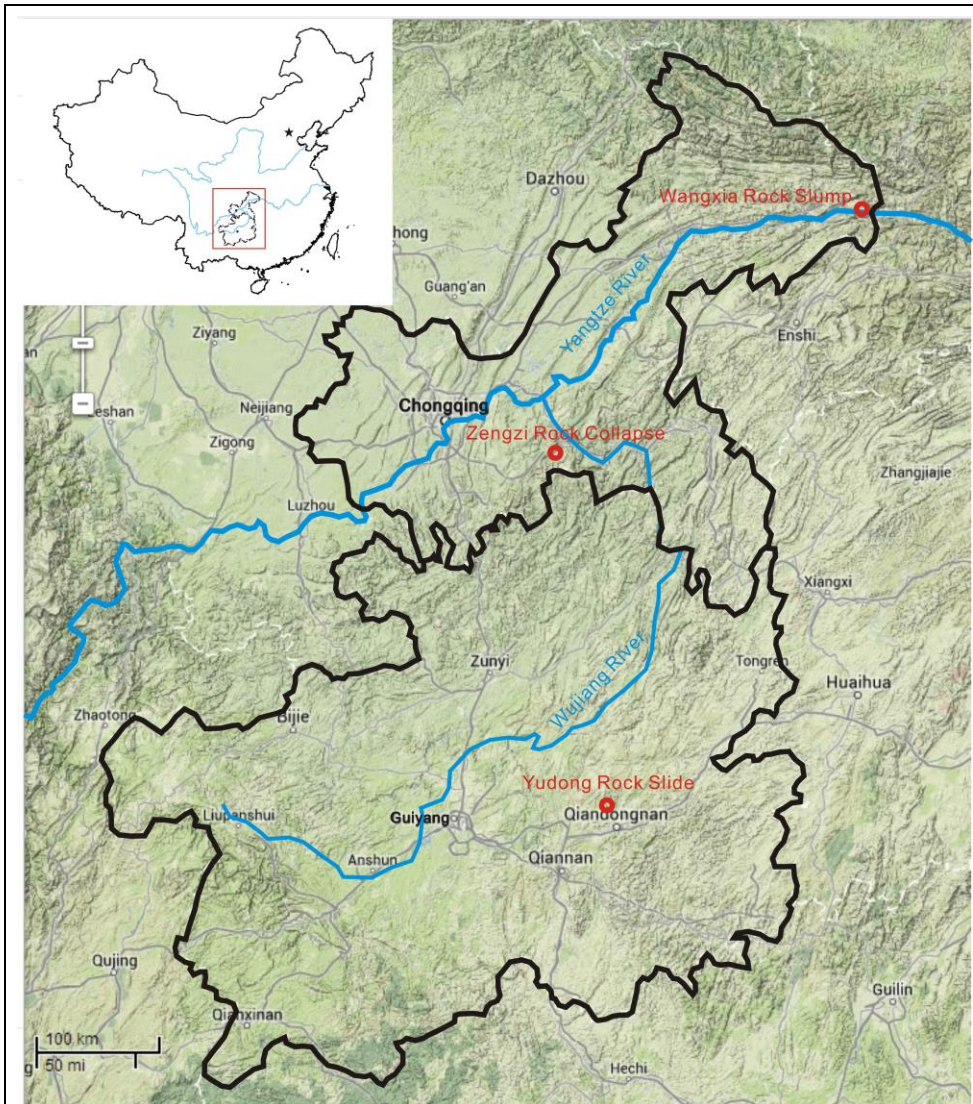A: Line 71-73 and relative references are added as proof of geo-hazards highly prone area.

Fig. 1 Locations of three rockslides: Wangxia Rock Slump, Zengzi Rock Collapse, and Yudong Rock Slide.
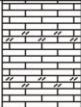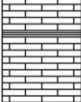
System	Series	Symbl	Column	Thickness	Lithology
Triassic	Lower	T_1^2		520~650m	layered limestone and dolomite, usually in cliff landform.
		T_1^1		660~680m	mudstone, layered limestone, dolomitic limestone, locally contains shale bands.
Permian	Upper	P_3^2		95~134m	layered limestone, usually be shaped into cliffs.
		P_3^1		98~143m	layered to blocky limestone rock, underlain by a measure of claystone, shale, and coal seams
	Middle	P_2^3		203~377m	layered to blocky limestone rock, interbedded with carbonaceous shale, usually cut by conjugate joints and in cliff landform.
		P_2^2		47~106m	thick layered limestone, interbedded with argillaceous bands, usually cut by joints and in cliff landform.
		P_2^1		2~13m	claystone, carbonaceous shale, interbedded with coal seams, bauxite, shaped into steep slope under the hard cap rocks
Silurian	Middle	S_2		500~680m	shale, silty shale, easily weathered and usually in a landform of gentle slopes

Fig.2 The most common outcrop sequence in southwest calcareous China

Many layers of carbonate rocks were deposited from Permian until Triassic time, and were interbedded with weak planes or soft strata (Fig.2). 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 argillaceous layers. The strength of carbonaceous shale sandwiched in the P_1 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,

批注 [I5]: The "argillated" is replaced by "argillaceous"

批注 [I6]: Q: The geological age should be marked consistently only using symbols or texts.
A: The texts are replaced by symbols.

90 et al. 1990). The weak interlayers play a significant role in mass movement. When soft strata

91 underlie hard rock, the yielding of the soft base may cause the uneven subsidence of the cap rock.

92 Lateral spreading and slumps with backward tilting are caused by this type of destabilization

93 mechanism, in which failure propagates uphill.

94 In the southwestern calcareous area of China, coal measures are common soft strata, accompanied

95 by thick carbonate sequences. Except for coal seams, the coal measures are usually composed of

96 associated interlayers of shale, carbonaceous shale, pyrobituminousshale, and bauxitic claystone.

97 Mining is active in these coal measures using the techniques of room and pillar mining and

98 longwall mining. The depth of cover ranges from dozens to hundreds of meters. It is believed that

99 underground mining activities can change the engineering geological conditions and reduce the

100 stability of cliffs (Tang, 2009; Altun, et al., 2010; Marschalko, et al., 2012; Lollino, et al., 2013），.

101 Cliff failures and the resulting catastrophes, examples of which are discussed below, are related to

102 underground mining.

103 Karstification is a significant factor when discussing the reasons for carbonate slope failure. It

104 particularly affects steeply inclined faults and tectonic joints and slowly widens the discontinuities

105 to create large open fractures, which foster rockslides (Santo el al., 2007; Parise, 2008). In

106 addition, the karstification process can cause a significant reduction in the mechanical properties

107 of the carbonate rock mass. This is very important for toe-constrained slides, which depend on the

108 strength of the rock mass at the toe. In some cases, the underground karst voids play the same role

109 as goaf, and cavern breakdown may also lead to landslides (White, et al., 1969; Parise, 2010).

110

3. Failure modes

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

3.1 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. 3). 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.
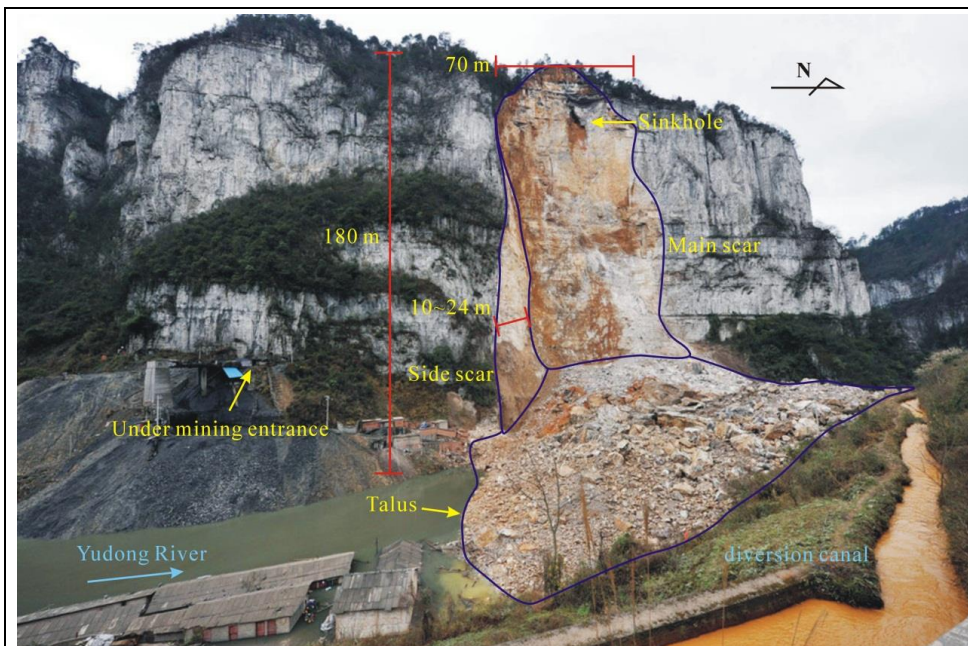

Fig. 3 Photograph showing an overview of Yudong rock slide I.

The Yudong Escarpment is about 220 m high and the slope angle is more than 80°. The steep

123   slope faces in the direction SE100°–130°, and the dip direction is NW325°, with slightly inclined

124   bedding. The outcrop consists of thickly bedded P_2^2 limestone and underlying P_2^1 coal measures.

125   The Yudong Escarpment lies in the gentle eastern flank of the Yudong Syncline, which strikes

126   NNE. As a result, a set of NNE-trending joints and a conjugate set of NW-trending joints are

127   present in the rock mass. The orthogonal $130°\angle70°$ and $80°\angle75°$ joints cut the $325°\angle9°$ rock

128   beds into prism- and tower-shaped blocks on the edge of the cliff. The jointed limestone is

129   moderately weathered, and the uniaxial compression strength of intact rock reaches 30 MPa. The

130   coal measures are composed of thickly bedded argillaceous shale and coal seams. Coal extraction

131   has been active in the soft basal unit, and the goaf is about 200 m deep behind the cliff face. The

132   "2.18" Yudong rock slide originates from one of these unstable blocks with a volume of about 30

133    $\times 10^4$ m^3. Several types of karst are observed in the rock slide area, including sinkholes, karst

134   tunnels, and dissolution fissures. A remote sensing image taken the day after the rock collapse

135   shows a sinkhole at the crest with a diameter of 2.2 m immediately behind the fall. The pipe flow

136   in the tunnels and cracks induce static and dynamic pressure, acting on the unstable rock block

137   and changing the stability. However, because of abundant vegetation, the sinkhole is not visible in

138   a previous image that was taken in the summer of 2012 (Fig. 4). The intense karstic erosion of a

139   yellowish-orange color has been observed on the vertical scar. The selective karst widens and

140   connects the pre-existing steep joints so that the area of the rock bridge covers less than 30% of

141   the main scar (Huang, 2013). The directed scratches indicate the brittle failure of the rock bridges

142   and consequent fall of the rock mass. The rock slide left two scars originate from joints. The main

143   scar is nearly parallel to the cliff face and about 80 m wide. The upper part of the main scar is a

144   sub-vertical plane, and the lower parts are planar and dip out of the cliff. The conjugate side scar is
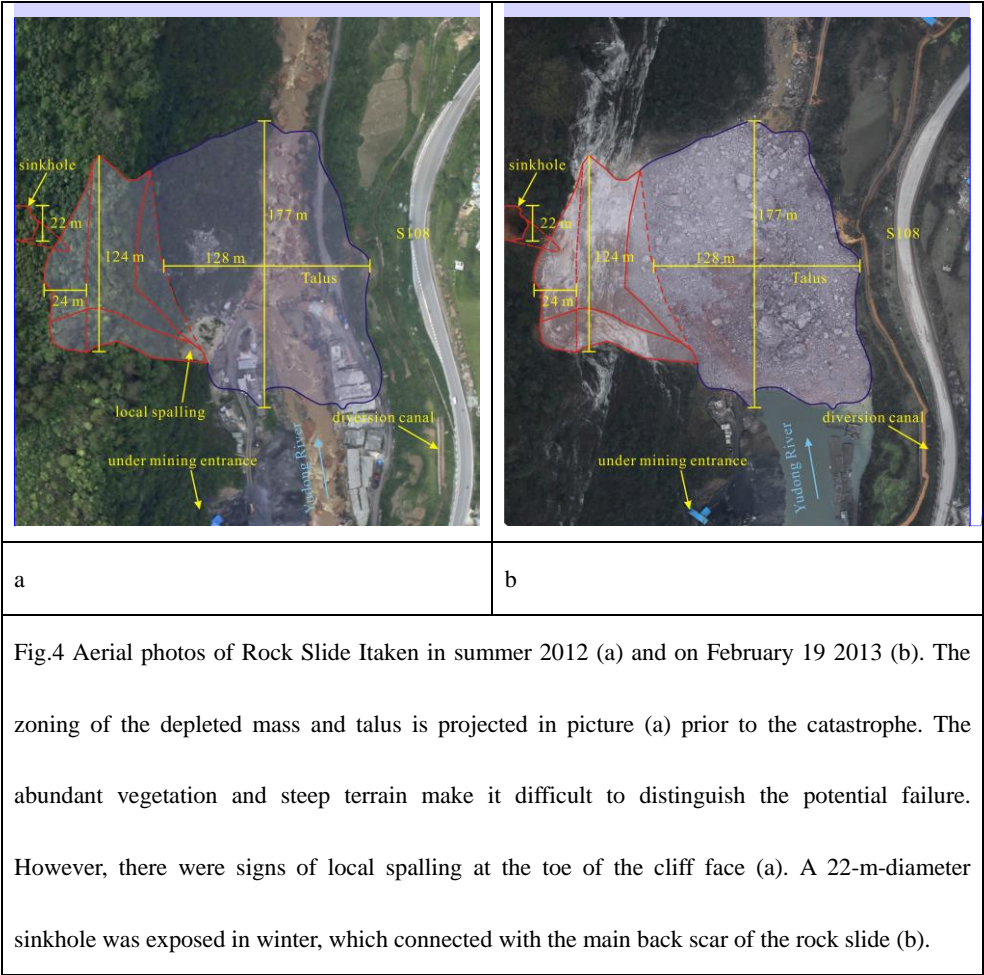
批注 [I9]: Q:I suggest that this highlight sentences move behind the explanation of its tectonic and its structural planes.
A: The sentence is moved behind as suggested.

批注 [I10]: Q: I am not sure what it means.
A: It is rewritten as in the text.

145 about 24 m wide and perpendicular to the cliff face (Fig.3).

| a | b |

Fig.4 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).

146

147 Another massive rock slide (II) (Fig. 5) occurred on April 16, 2013, about 100 m away from the

148 February 18 rock slide (I). The morphology of the vertical scar of rock slide II is similar to that of

149 rock slide I. The lower rupture surface forms a steep and irregular scar (Fig. 6). These two rock

150 slides have the same failure mechanism of a steep back scar separating the unstable block from the

151 escarpment and the block breaking through the toe leading to free fall of the rock mass. The

152 rupture surface implies a plane slide involving shear failure through the rock mass. There is little

153 or no shear displacement along the rupture surface, and the velocity is very high. The brittle

154   failure of the rock mass in the toe area can be explained by the brittle failure of the rock mass

155   under uniaxial compression tests. In other words, it is largely dependent on the mechanical

156   properties of the rock mass at the toe. The toe is sheared along random discontinuities of limited

157   persistence traced by the rupture surface (Fig. 7).

Fig. 5 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.
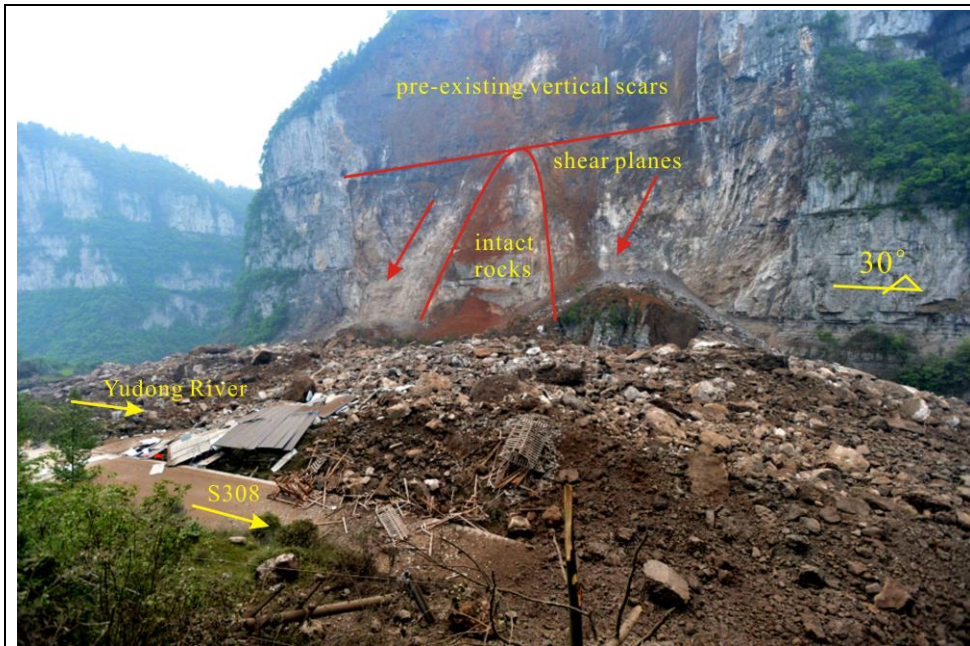
Fig. 6 Photograph showing rock slide II at Yudong. The pre-existing vertical scars are coated with karst of a yellowish-brown color, while the rupture surfaces are white and gray, indicating brittle failure and planar sliding through the limestone.
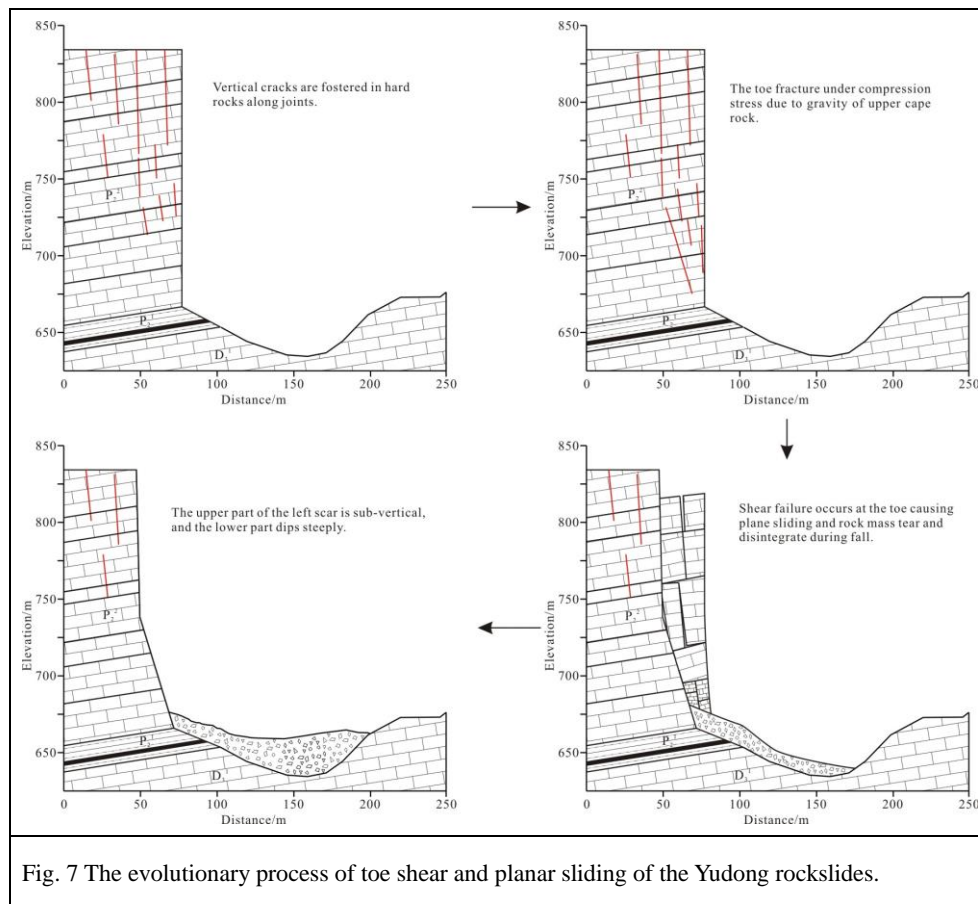
Fig. 7 The evolutionary process of toe shear and planar sliding of the Yudong rockslides.

158

3.2 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. 8). 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_2 silty shale forms a soft base and a gentle slope (20°–30°). Talus occurs everywhere under the cliffs,

168   indicating that cliff failure occurs as scarp retreat.

Fig. 8 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.
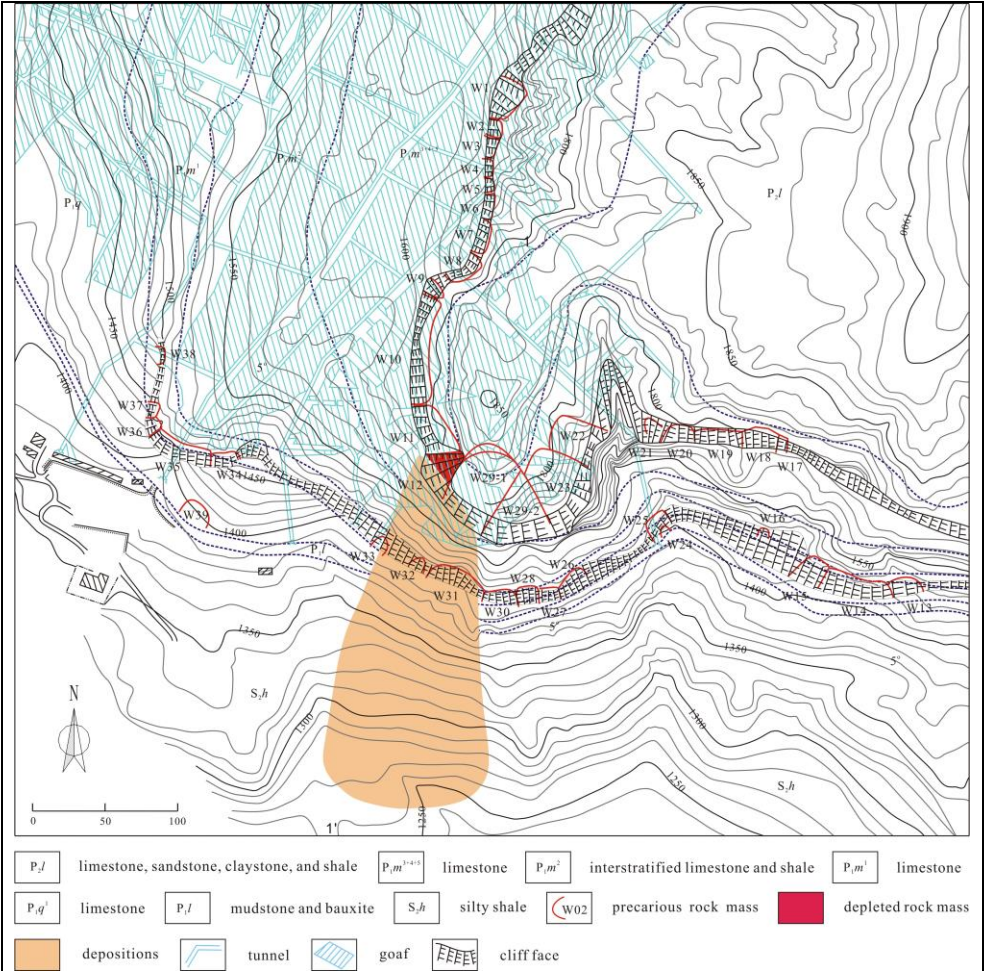
169

170   Rocks frequently fall in the Zengzi Cliff area. On August 12, 2004, a massive rock collapse

171   occurred in the upper platform, which is about 200 m high (Fig. 9). The depleted mass is a prism

172   block shaped by sub-vertical joints and bedding. Two vertical back scars and a groove surface in

批注 [I13]: Q: the depositions shadow is seem to somewhere strange, because the slope direction is SWW, but the shadow direction is just S, so i think the shadow range need to modify.
A: The depositions is in the right place and it did turn to the south when it fell down to the slope surface.

173   the underlain soft strata are exposed after the collapse. Large areas of the scars are coated with

174   karst argillaceous fillings and yellowish-orange calcite, while the rock bridge failure scars are

175   fresh. Field investigations showed that the head scars are wide open prior to the massive collapse.

176   Seepage forces and frost from percolating water acted on the prism block over a long time and

177   influenced the stability; however, only karst could alter the conditions in the rock adjoining the

178   slope by increasing the connectivity of back scars. The underlying soft strata consist of alternating

179   beds of thin-bedded shale and medium-bedded limestone, and as a result of weathering, form a

180   40-m-high slope.

| a. Elevation view of Zengzi Cliff | b. Side view of the rock collapse |

Fig. 9 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.
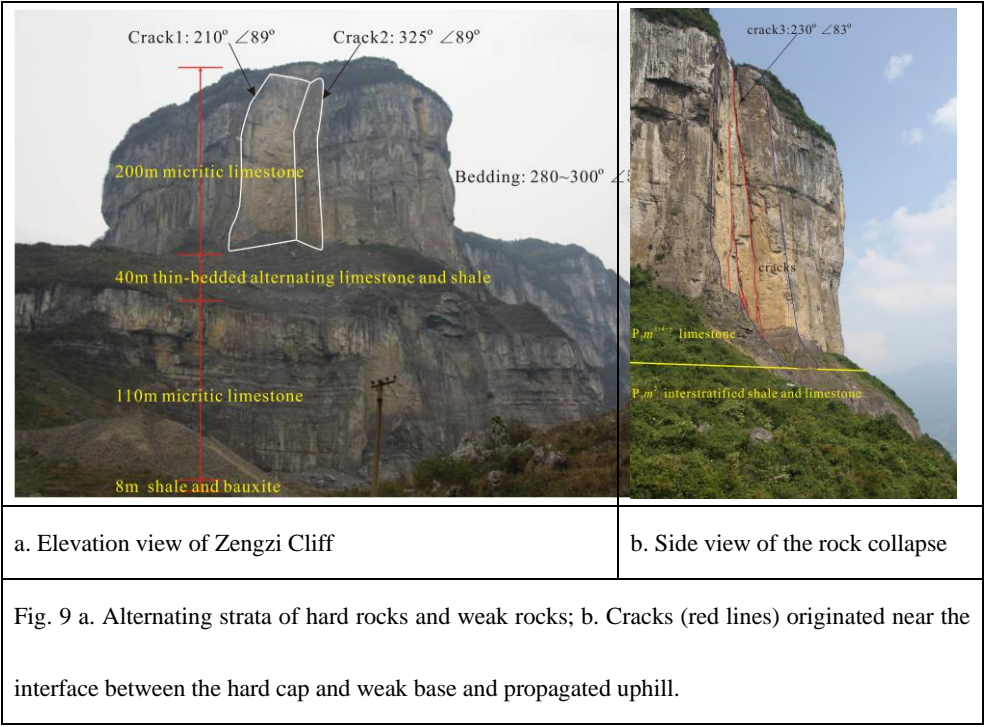
181

182   Mining activity has been conducted for decades, but community monitoring started in 2001.

183   The opening velocity of the head scar was very slow from 2001 to 2003 (Ren, 2005). It increased

184   to 4–15 mm/10 d in the period between April and July 2004 (Fig. 10), and signs of pre-collapse,

185 (rock falls) were repeatedly observed. At that time, the government issued warnings and evacuated

186 residents and workers. The velocity abruptly increased from August 10, and the increment reached

187 658 mm on the last day. The process of the Zengzi rock collapse was captured on video: the tower

188 dropped vertically and disintegrated while falling. It is unusual that the failure initiated in the

189 bottom of the hard block rather than the underlying soft strata. The splitting of the hard rock mass

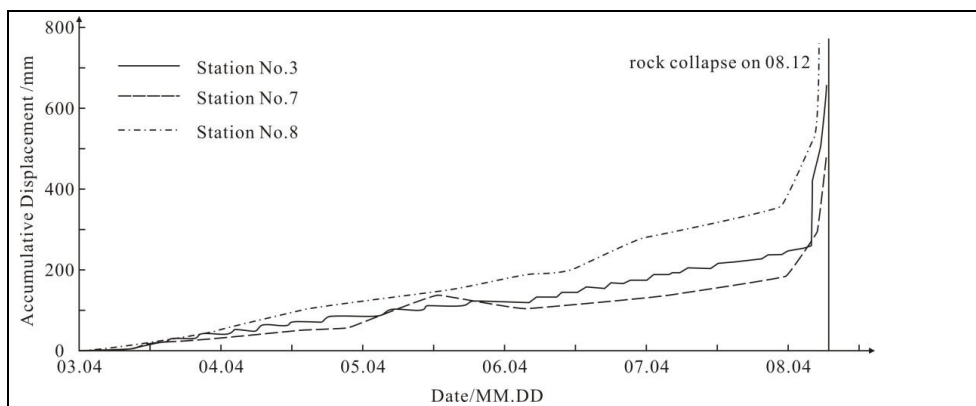190 at the toe led to tower collapse. The curved surface in the soft strata will have been carved by

191 collision.

Fig. 10 Cumulative displacement of monitoring stations at the crest of Zengzi Cliff in 2004 (Ren, 2005).

192

193 Tensile splitting has been observed in uniaxial compression tests of rock samples with high

194 brittleness and strength, such as limestone. There are several reasons why the collapse did not start

195 with shear failure in the underlying strata. The rock mass in the bottom of the tower block is in

196 poor condition: fractured and weathered. Drill cores obtained strongly karstic rock containing

197 dissolution pores, caves, tufa, and calcite. The drilling also revealed at least 11 fissures, some of

198 which were filled with yellow clay (107 Geology Team, 1995). This is because the underlying

199 strata are low-permeability soft rocks; hence, there are steady water flows immediately above.

200   Furthermore, the soft strata are not sufficiently weak. These strata consist of interbedded thin

201   layers of shale (0.1–0.2 m) and medium-thick limestone. The tower block could easily shear

202   through the shale but not the intercalated limestone. Under these circumstances, tensile split

203   failure of the tower bottom is a reasonable failure mechanism, involving compression fracturing

204   and horizontal shearing in the shale beds (Fig. 11). Field studies and deformability tests on rock

205   masses all around the world have demonstrated that folded and flat-lying rock masses are prone to

206   tensile splitting near thin weak planes. Compression fracturing and tensile splitting are important

207   failure mechanisms for sub-horizontally bedded slopes. The Zengzi cliff collapse exposed back

208   scars in the nearby deformable rock mass, which propagated uphill (Fig. 9b), and a fractured rock

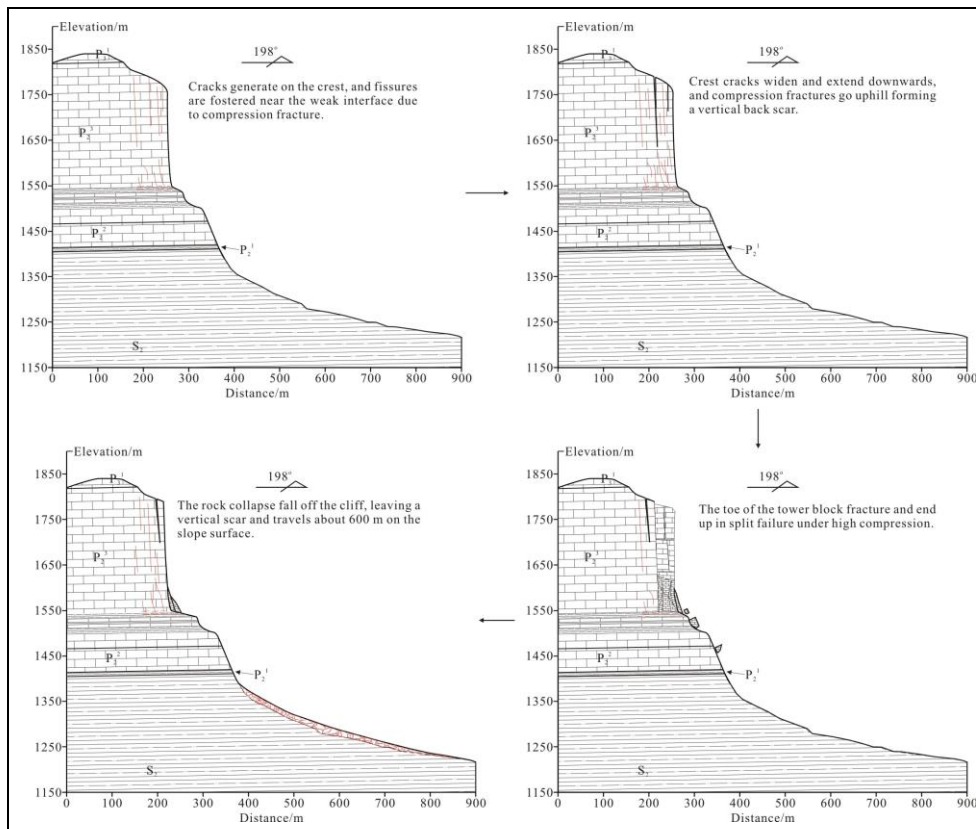209   mass was observed near the shale interface.

Fig. 11 Failure process of the Zengzi rock collapse, involving toe splitting and tensile failure.

3.3 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 left bank of the Yangtze River in Wushan County of Chongqing, about 1000 m above the water level (Fig. 12). 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 P_3 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.

批注 [I14]: Q: left or north
A: It is revised into "lfet"

批注 [I15]: Q: The geological age should be marked consistently only using symbols or texts.
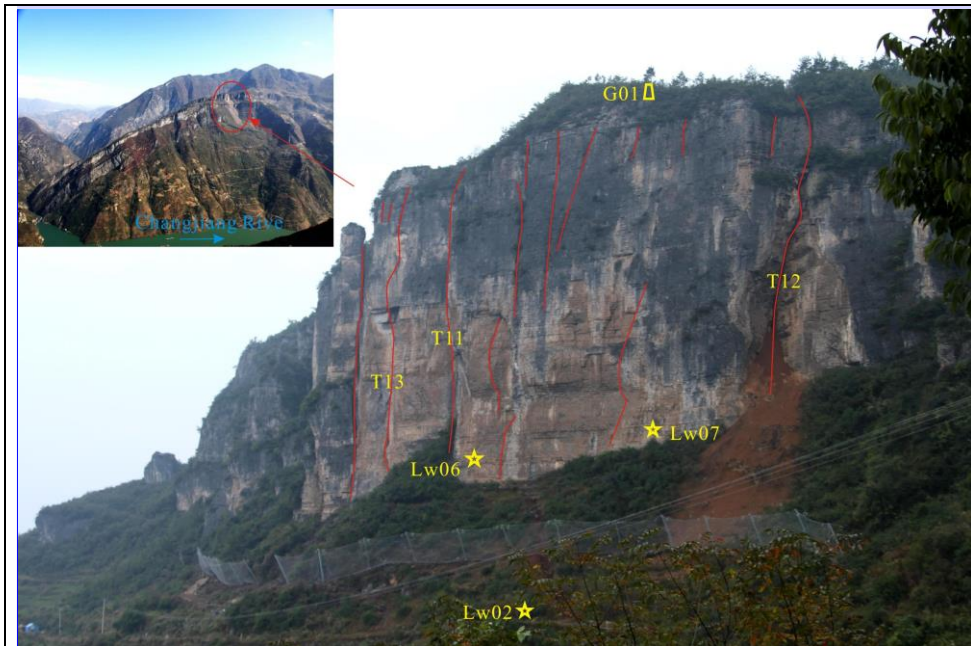A: The texts are replaced by symbols

Fig. 12 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.

223

224 The slope movement can be traced back to June 18, 1999. Four collapsecraters and nine cracks

225 were observed in the crest area after 108.5 mm of rainfall on June 15 and 16 (Le, et al., 2011).

226 Intensive deformation began on August 21, 2010, after four days of concentrated rainfall. Rep

227 eated pre-collapse signs were observed. Crown cracks widened, and new cracks occurred on the

228 crest. Rocks fell off from the cliff face and vertical scars in the rock mass. In addition, gravelly

229 soils flowed out from steep cracks at the toe. Transverse ridges and cracks were observed on the

230 country road beneath. The mass movement accelerated as a result of 70 mm of precipitation from

231 October 10 to 13. The fissures in the isolated blocks extended and widened. Rock falls became

批注 [S16]: Q: the flow direction is wrong.
A:The flow direction of the Changjiang River is revised (in the top left corner).

232   more obvious both in volume and frequency. Finally, a massive rock slump occurred on October

233   21, in which the isolated prism slid downhill, breaking through the toe and leaning against the

234   back scars. The underlying weak rocks were squeezed out and scattered over the slope surface.

235   Displacement monitoring showed that the crest was dominated by subsidence, while the horizontal

236   and vertical displacements were about the same at the base. The incompetent base showed

237   horizontal movement and little subsidence (Fig.13). These phenomena were caused by ductile

238   yielding and rotational shearing in the incompetent base (Fig. 14). The squeezing out contributed

239   to the uphill propagation of cracks and disintegration of the mountain into slab- and prism-like

240   blocks.

Fig. 13 Cumulative displacement at monitoring stations at the Wangxia rock slump (Le, et al., 2011).
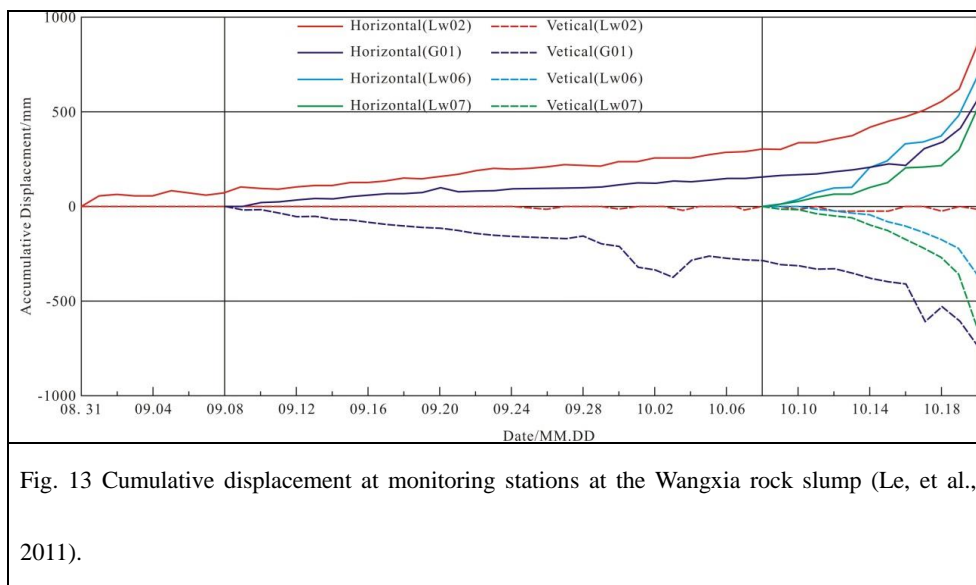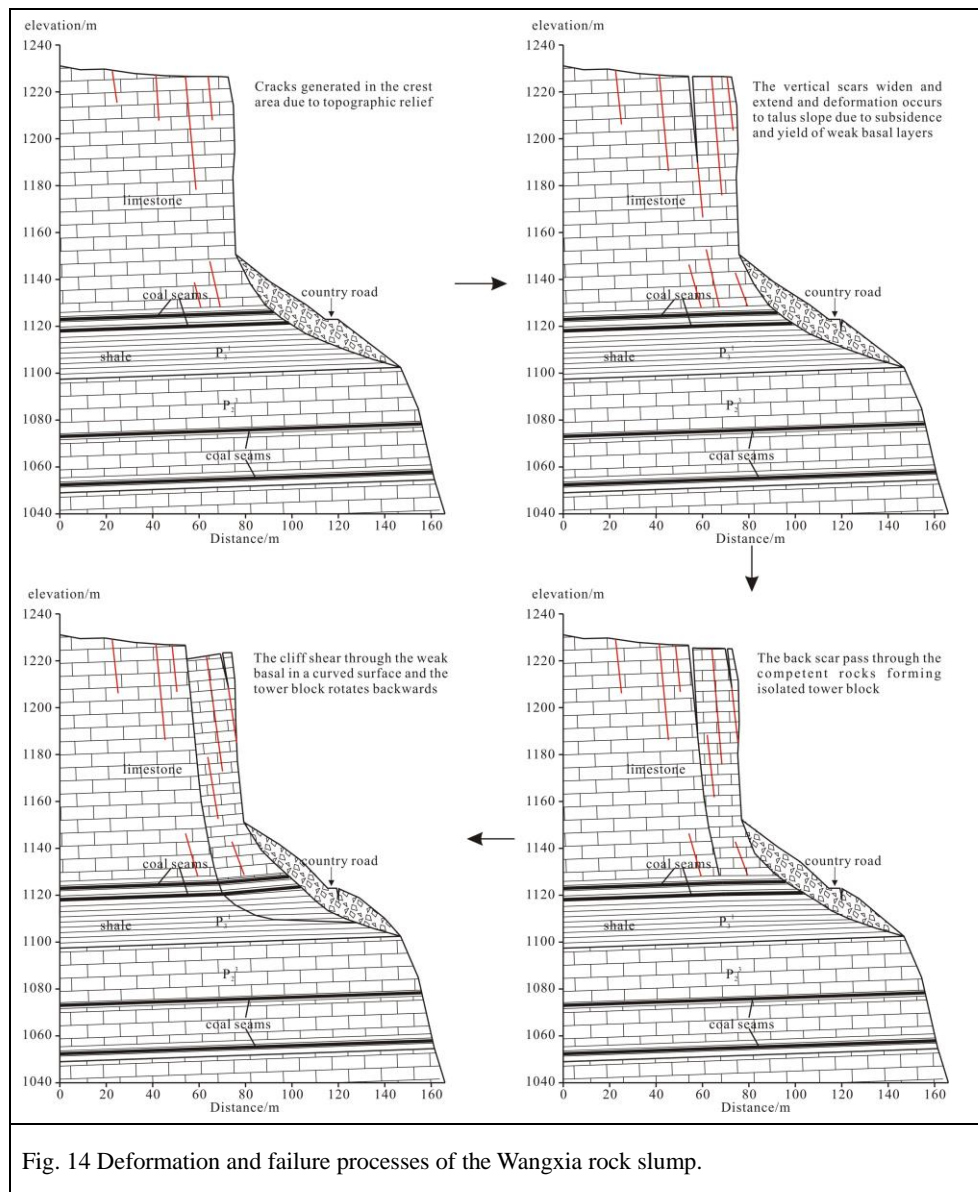
Fig. 14 Deformation and failure processes of the Wangxia rock slump.

241

242 It is worth mentioning that there is a good correlation between the acceleration of displacement

243 and concentrated rainfall. Because of cracks and fissures in the limestone, water could easily and

244 rapidly percolate into the weak strata. The unconfined compressive strength (UCS) of the shale

245 shows a substantial decrease when saturated, and the softening factor is about 0.62. However,

246 there is a 2–4 day time lag between concentrated rainfall and acceleration of displacement,

247 because the infiltration of water into poorly permeable shale takes time.

248

4.   Numerical back-analysis

250 Numerical analysis is a sophisticated method for assessing the potential failure modes of rock

251 slopes. We use it herein to validate the cases discussed above, which show different failure

252 mechanisms for sub-horizontally bedded cliffs (compound slide, rock collapse, and rock slump)

253 and to explain the backgrounds to the slides. The computation was performed using the computer

254 program UDEC. As discussed, the Yudong rock slide and Wangxia rock slump are characterized

255 by thick shale underlying the cap rock. However, the base of the Zengziyan consists of limestone

256 interbedded with thin shale bands. The calcareous shale in Yudong slide possesses a relatively

257 high strength and the thin shale bands, containing talcum, in Zengziyan collapse is easiyly

258 weathered and weak. The strength of the carbonaceous shale in Wangxia is moderate comparing to

259 the others. The parameters used in the simulation are given in Table 1.

260 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

批注 [I17]: Q: If you do not discuss or figure out the difference of the three example, the numerical model will be seen to sudden, and it is not easy to understand why the three are different.
A: A short discussion is presented from line 254-259 to explain the difference of the weak strata between these cases.

Tensile strength of rock mass (MPa)	0.3	0.1	0.04	0.04
Friction angle of joints (⁹)	30	25		
Cohesion of joints (MPa)	1.0	1		
FOS	-	1.01	1.21	1.07

261

a. Toe shearing and plane sliding.	b. Toe splitting and collapse.	c. Rotational shearing and slumping.
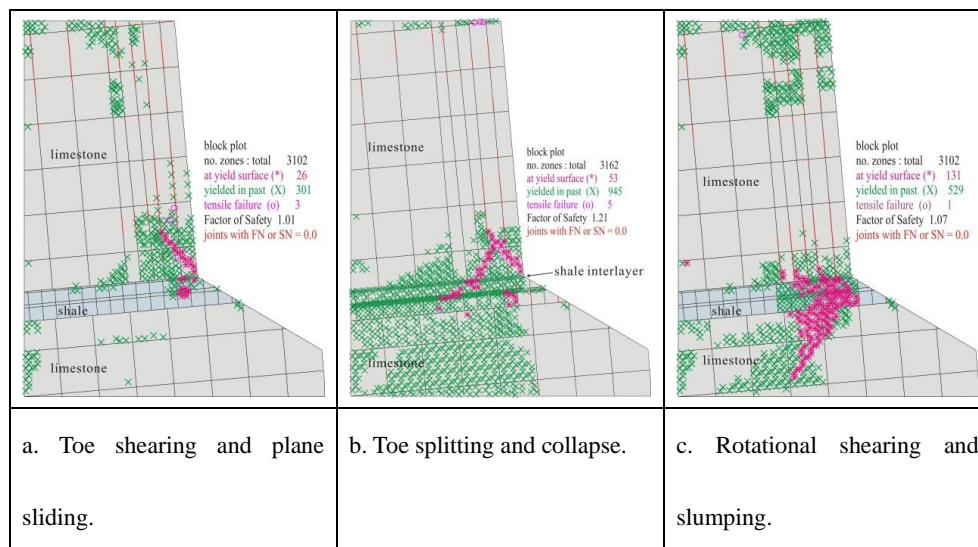
Fig. 15 Plastic state and joint opening for rockslide initiation in cliff slopes.

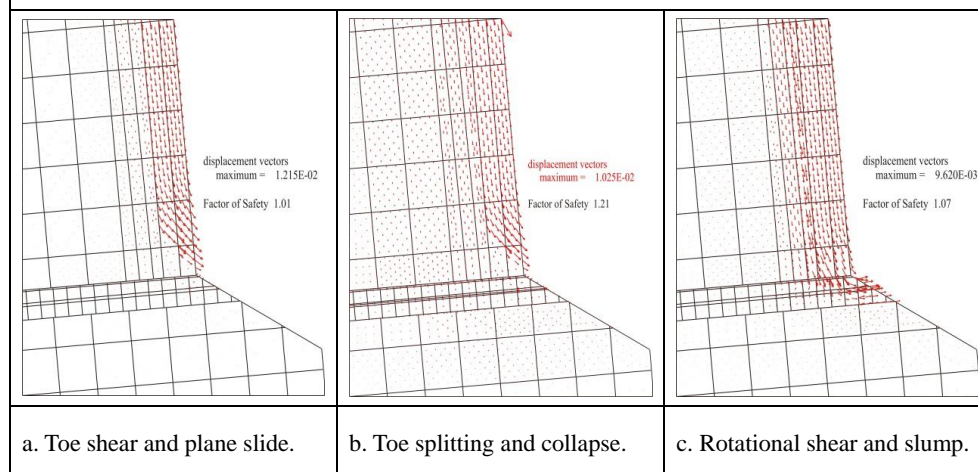| a. Toe shear and plane slide.	b. Toe splitting and collapse.	c. Rotational shear and slump.

Fig. 16 Displacement vectors of the initial failures of cliff slopes.

262

263   The natural stress field is characterized by a tensile zone on the crest and stress concentration at

264   the toe. When a thick incompetent basal layers is present, the jointed slope tends to fail as a slump.

265   A yielding curved surface gradually emerges in the basal layers under long-term gravitational

266   compression of the upper cap rock. A large plastic zone is present in the weak basal layers and

267   nearby hard rock mass (Fig. 15c). The horizontal movement of the weak stratum is prominent.

268   Pre-existing joints in the hard rock mass widen upward and slip with the ductile flow of the basal

269   layers. The movement of the massive unstable rock mass is dominated by subsidence in the crest

270   area and back tilting at the toe (Fig. 16c).

271   When the weak basal is a thin interlayer, rotational slide through the toe is unlikely to occur. The

272   horizontal shear stress determines the possibility of shear failure in the beds. For a sub-horizontal

273   bedded slope with gentle tectonic disturbance during geologic evolution, the horizontal to vertical

274   stress ratio is generally less than 1 (Zhang, et al., 1994). This indicates that it is possible for a

275   weak interlayer with a frictional angle less than $45°$ to shear horizontally. Under these

276   circumstances, the plastic zone ranges over the interlayer as well as the overlying competent rocks.

277   The rock mass at the toe is in a plastic state as a result of compression fractures. Two yield

278   surfaces dipping in opposite directions are formed (Fig. 15b), similar to tensile failure behavior for

279   some brittle rock samples. The displacement prior to collapse is limited, and remarkable squeezing

280   out is unlikely to be observed in the toe area (Fig. 16b).

281   A rock slide might burst out in hard rock where back scars cut through, and no discontinuities or

282   weak strata are exposed at the toe. Irregular scars caused by brittle and shear failure through rock

283   mass dip out of the cliff faces. The yield zone is mainly located at the block toe but not in the

284   underlying rocks (Fig. 15a). The fracture of the toe rock mass gives rise to joints opening

285   immediately above. Numerical computation gives a plane yield surface at the bottom of the

286   separated block, which is called a potential failure surface (Fig. 16a). A small displacement

287   appears before the outbreak of a compound slide. However, ground fractures on the crest and

288   spalling in the toe area might occur.

289

290   **5.   Underground mining**

291   The failures at the three locations described above are related to large areas of mining out. Pells

292   (2008) used a 2-D continuum model to assess macro-scale movements of cliff faces caused by

293   total extraction and proved that the steep slope tends to tilt outwards when mining occurs beneath

294   the cliff, and extraction well behind the cliff face causes back tilt. Our similar simulations are

295   shown in Fig. 16. The rock slide model in Fig. 14a was adopted. The roof tends to collapse, and

296   the surrounding rocks gradually fracture. The undermining-induced subsidence of the crest causes

297   the dilation and tensile failure of the rock mass (Fig. 17a). The FOS decreases from 1.01 to 0.98

298   when the underground mining is located behind the cliff face. When the extraction is directly

299   beneath the cliff, the rock mass is subjected to a small constraint; hence, cliff failure break-out

300   through the fractured rock mass between the goaf and open face is feasible (Fig. 17b). The

301   maximum principal stress on both sides of the goaf increases while that of the overlying rocks

302   decreases (Fig. 17c).

批注 [I18]: Q:I believe the under mining simulation is more like the Case 1 (Yudong Slide), what do you think how under mining affects the other two cases?
A: These three cases has a similar "hard on soft" landform and structure. The only difference is the rock mass at the toe which has been taken into account in the simulation. So that the simulation is adequate to assess under mining effects in these cases.

批注 [I19]: Q: I assume you mean a 2D continua model?
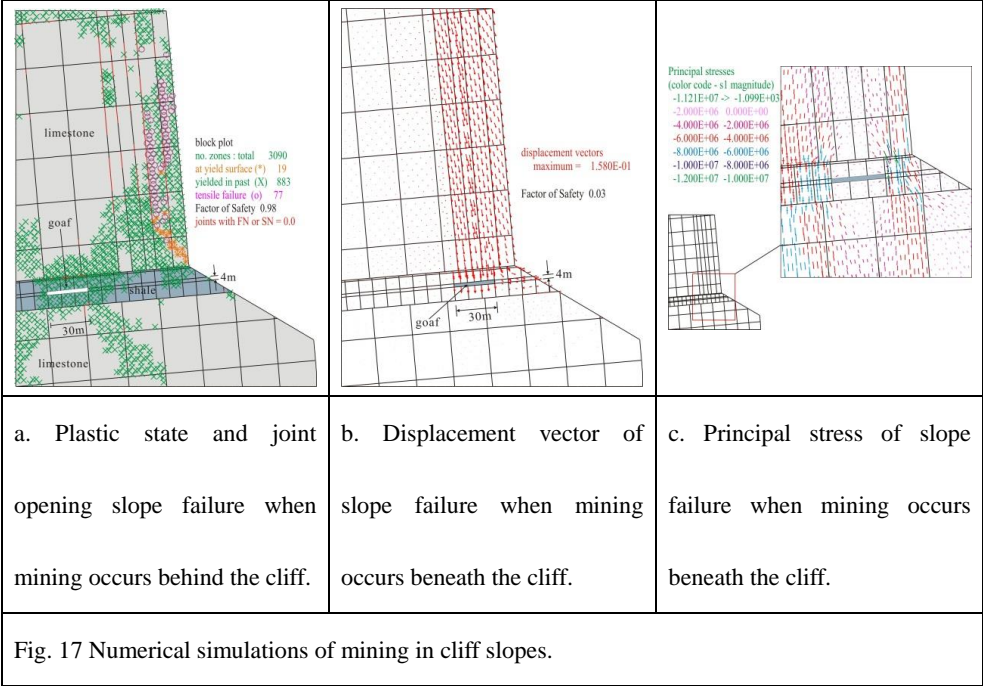A: Yes. The "continuum 2-D model" is replaced by "2-D continuum model".

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. 17 Numerical simulations of mining in cliff slopes.

303

6. Conclusions

304

305 In this study, three different examples of failure in sub-horizontally bedded limestone cliffs are

306 discussed. The failures are characterized by pre-existed vertical joints passing through thick

307 limestone. The Yudong rock slide originated in a limestone cliff edge and left a moderately

308 inclined rupture plane, implying shear failure through the hard rock. Rock collapse caused by

309 compression fracture and tensile splitting of the rock mass near the interface between the hard cap

310 and weak stratum occurred at Zengzi Cliff. The Wangxia cliff failure showed a slow rock slump

311 sheared through the underlying incompetent rock mass along a curved surface. The mechanism of

312 toe breaking mainly depends on the strength characteristics of the rock mass.

313 Considering that the rock mass near the cliff face is not laterally constrained, it is reasonable to

314 assume that the there is a massive UCS failure at the toe of the vertical tower and slab blocks.

315 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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