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## Mechanism on apparent dip sliding of oblique inclined bedding rockslide at Jiweishan, Chongqing, China

**Abstract** Because of the existence of a front stable rockmass barrier, the failure pattern of an oblique inclined bedding slope is conventionally recognized as a lateral rockfall/topple, and then a transformation into a rockfall accumulation secondary landslide. However, the Jiweishan rockslide, Wulong, Chongqing, which occurred on June 5, 2009, illustrates a new failure pattern of massive rock slope that rockmass rapidly slides along apparent dip, and then transforms into a long runout rock avalanche (fragment flow). This paper analyzes the mechanism of the new failure pattern which is most likely triggered by gravity, karstification, and the processes associated with mining activities. A simulation of the failure processes is shown, using the modeling software, FLAC<sup>3D</sup>. The results show that there are five principal conditions for an apparent dip slide associated with an oblique inclined bedding slope are necessary: (1) a block-fracture bedding structure. The rockmass is split into obvious smaller, distinct blocks with several groups of joints, (2) an inclined rockmass barrier. The sliding rockmass (i.e., the rockslide structure before movement) exists along a dip angle and is barricaded by an inclined stable bedrock area, and the subsequent sliding direction is deflected from a true dip angle to an apparent dip angle; (3) apparent dip exiting. The valley and cliff provide a free space for the apparent dip exiting. (4) Driving block sliding, which means the block has a push type of effect on the motion of the rockslide. The “toy bricks” rockmass is characterized by a long-term creeping that induces the shear strength reduction from peak to residual value along the bottom soft layer, and the sliding force is therefore increased. (5) The key block resistance and brittle failure. The pressure on the key block is increased by the driving rockmass and its strength decreases due to karstification, rainfall, and mining. The brittle failure of the karst zone between the key block and the lateral stable bedrock occurs instantaneously and is largely responsible for generating the catastrophic rockslide–rock avalanche. If there was not a pre-existing key block, the failure pattern of such the inclined bedding rockmass could be piecemeal disintegration or small-scale successive rockfall or topple. The recognition of catastrophic failure potential in such inclined bedding slopes requires careful search for not only structures dipping in the direction of movement, but also key block toe-constrained condition.

**Keywords** Oblique inclined bedding slope · Apparent dip slide · Key block · Bedding rockslide · Rock avalanche · Massive rock slope failure

### Introduction

On June 5, 2009, a huge catastrophic rockslide–rock avalanche (fragment flow) took place under a mass up to 60 m thick at the crest of the Jiweishan Hill in Wulong, Chongqing, China, with a long runout length of 1,500 m. Seven million m<sup>3</sup> moved towards the valley, disintegrated and covered an area of 0.47 km<sup>2</sup>. An iron ore mine was obliterated, with a loss of 74 persons (Qiang et al.

2009). This catastrophic slide occurred in a sequence of coal measure strata. The sole factor responsible for a catastrophic behavior was the apparent bedding orientation.

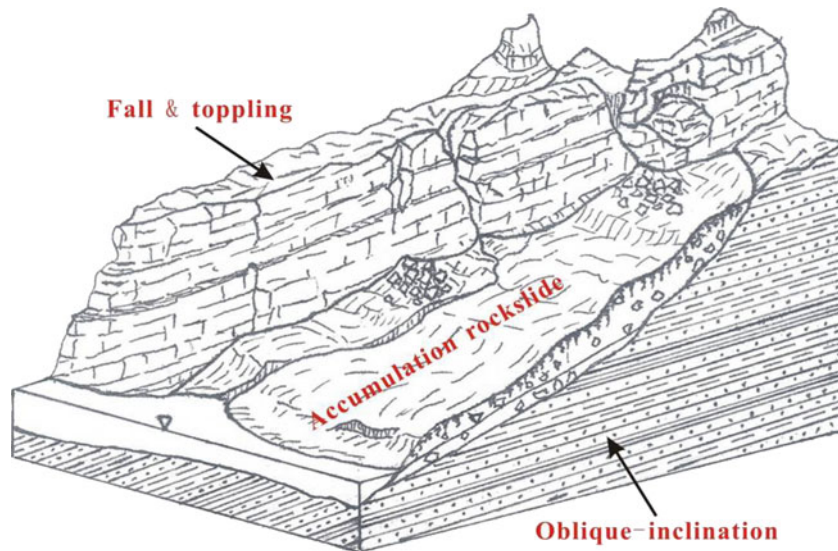
This massive rock slope with oblique inclined thick bedding structure is widely distributed in the southwestern carbanite rock areas of China (Yin, 2008) and the failure pattern is conventionally recognized as lateral fall or topple with a short runout distance. That is, due to the existence of a front barrier of stable bedrock, the rockmass laterally falls or topples first and subsequently accumulates on the lower gentler slope, and then converts into a rockfall accumulation secondary landslide induced by overload, rainfall, or other factors (Fig. 1). The Jiweishan Hill area has also been recognized as a rockfall risk zone since 1994, and many mitigation measures have been undertaken to reduce the rockfall hazard. These measures included the establishment of a monitoring warning system, the relocation of the village of 300 citizen in 2005, and the closing of the road within the risk zone 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–rock avalanche (fragment flow), and one this size was not expected to occur. In assessing the means for mitigating geohazards for The Jiweishan village, there have been four deviations from the planned scenario that occurred: (1) the failure pattern, was not a rockfall but a rockslide–rock avalanche with long runout; (2) the sliding direction did not occur in the predicted easterly direction but instead, progressed in a NNE–NW direction; (3) the volume was not 0.2 million m<sup>3</sup> but was actually, 7 million m<sup>3</sup>; (4) as for runout distance, the length was not the predicted 100 m but was much longer, at 1,500 m (Fig. 2, Table 1).

The instantaneous failure of the smaller front rockmass is the main reason a rapidly moving, rockslide was subsequently triggered. Many scholars have studied the stability of thick-bedded rockmasses in view of a primary, or “key block”. For example, Hoek and Bray (1974) put forth the concept of “keystone” and emphasized its controlling role in the stability of total rockmass; Shi (1981) presented the mathematical criterion for the stability of a key block by combing set theory and rockmass structure; and Yin et al. (2000) proposed the ideas and methods for stabilization of the key block.

The above studies mainly regard the key block as a separated wedge, but in fact, the instantaneous rupture of the key block along the karstified zone and the sliding of “driving rockmass” along an apparent dip exist, as in the example of the Jiweishan rockslide–rock avalanche. Hungr and Evans (2004) distinguishes block slide with toe breakout (toe-constrained slide) that some structurally controlled rockslides exploit discontinuities which do not daylight at the toe, so that the rupture surface must break out through the rock mass and the behavior of these slides depends on the rock strength, similar to the distinction between slow slumps in weak rocks and collapses in strong rocks. Of special

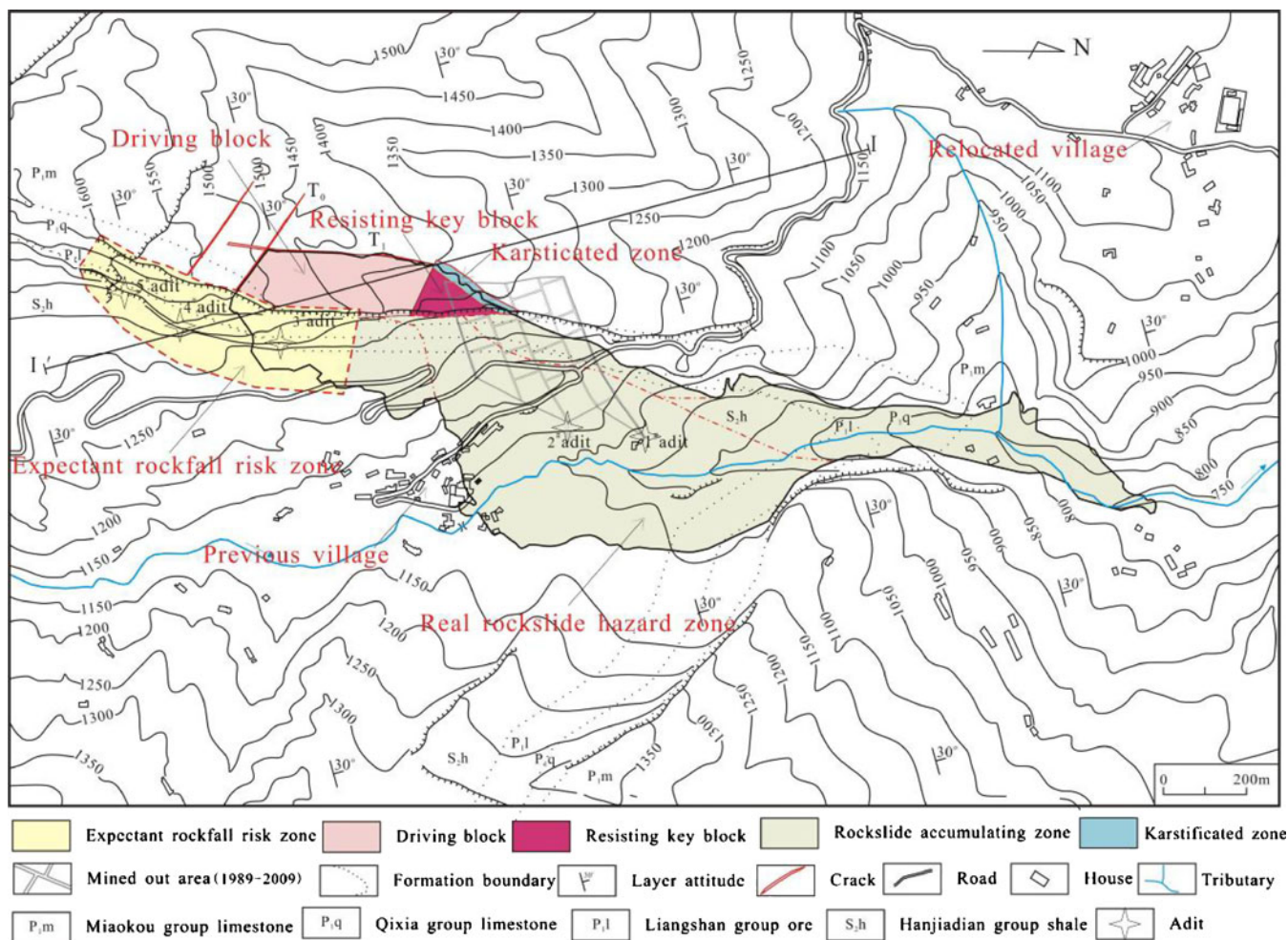
**Fig. 1** Schematic diagram shown oblique inclined bedding slope



concern are slides involving a combination of a steep planar weak surface and a short toe breakout zone in strong rocks. The extent of the disaster caused by the rapid long runout avalanche is very difficult to predict. Hungr (2006) proposed that runout estimates are preferably derived by an empirical approach, calibrating

simple rheological models by means of back analysis of existing cases.

In spite of that, the knowledge about the mechanism of a key block for apparent dip sliding of a declined bedding slope is incomplete. Herein, the failure pattern for an oblique inclined



**Fig. 2** Layout map of the expectant rockfall and the real rockslide–rock avalanche (fragment flow)

**Table 1** Comparison of the real occurrence with the expectation of the prevention preparedness of geohazards

	Expected result	Real result
Failure mode	Rockfall	Rockslide
Runout	100 m	1,500 m
Sliding direction	East	North
Volume	0.2 million m <sup>3</sup>	7 million m <sup>3</sup>

thick bedding slope is studied by analyzing the geological settings, the influence of mining, and finite difference simulation by using the software FLAC<sup>3D</sup>.

**Geological settings and mining**

An oblique inclined bedding slope is a particular pattern of inclined bedding slope in which the creeping and sliding direction of rockmass is changed from the true dip angle at the beginning to the apparent dip as a result of a barrier of stable bedrock in front of the slide(Figs. 3, 4 and 5). Generally, the tendency of the layer is between reversed slope and inclined slope and the dip angle is less than the gradient of topography. This massive rock slope has a typical “dualistic structure” with rock complexes of higher strength overlying those of lower strength, i.e., the steep rigid rock layer of more than 100 m at the upper part and gentle soft layer of less than 15 m underneath. In geology, the slope mainly occurred at the two wings of NE fold axes formed by Late Paleozoic carbonate formation with a dip angle of 15~35°.

The typical structure pattern of slopes has been studied in the Three Gorges area of China (Yin, 1994). The slope is made of so-called coal measure strata. The thick-bedded limestone with intercalations of six types of carbon or argillaceous shales is 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 10,000 m<sup>3</sup>. The thickness of the shale soft layer intercalations varies between 10 and 30 cm. Beneath this, is a shale stratum containing coal, iron ore, or bauxite with about ten or

more meters thick that has been often excavated out in the course of hundreds of years of mining (Fig. 6).

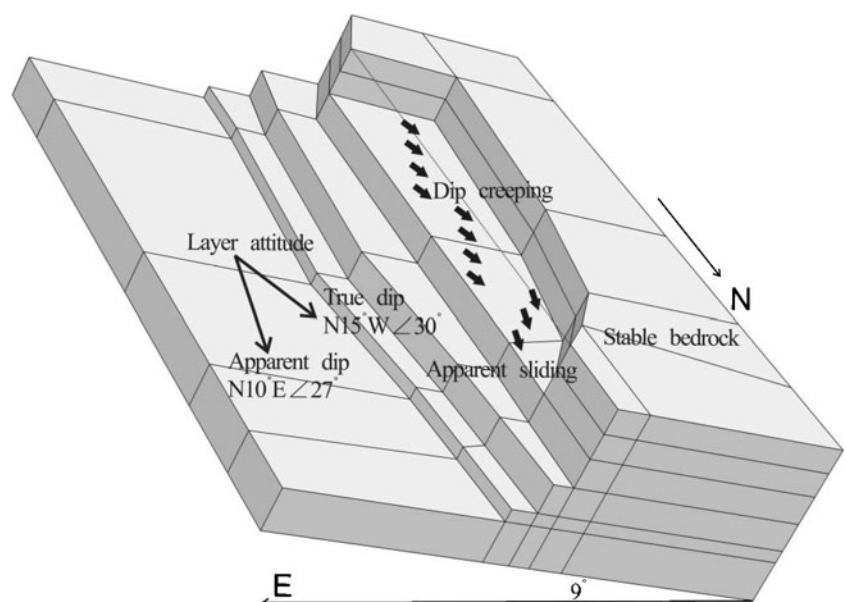
The structure of the slope in the Jiweishan Hill is the same as the above mentioned slope (Fig. 7, see also in Fig. 5). The detailed descriptions for formation of The Jiweishan Hill from top to bottom are as follows:

1. Maokou Group (P<sub>1m</sub>) of the upper part of the Lower Permian System. It is made mainly of gray thickly bedded micro-crystalline limestone with a thickness of about 50 m.
2. Qixia Group (P<sub>1q</sub>) of the middle Lower Permian System. It is made dominantly of dark gray and gray medium-layered bituminous limestone with a thickness of 90~130 m, inter-bedded with calcareous shales.
3. Liangshan Group (P<sub>1l</sub>) of the lower part of the Lower Permian System. It is composed of hydromica-claystone including hematite, with a total thickness of 10~14 m and an iron ore layer thickness of less than 2.0 m. The P<sub>1l</sub> stratum is exposed at the foot of the eastern cliff.
4. Hanjiadian Group (S<sub>2h</sub>) of the lower Medium Silurian System. It is made of grayish-green silt mud shale.

Figure 7 indicates that the Jiweishan Hill is a cuesta, with a height difference of 450 m and a slope gradient of 20~40°. The attitude of bedrock is N 75° E/345°<21~35° with intercalations of multi-layered carbon or argillaceous shale.

The slope is fractured by two sets of dominate steep joints with smooth interface. One is a “compressive joint” parallel to the strike

**Fig. 3** Deflected angle between true dip and apparent dip of oblique inclined bedding slope





**Fig. 4** Oblique inclined bedding slope of the Lianziya at the Three Gorges (Colluvial landslide is formed by lateral rockfall)



of bedrock with an attitude of  $N 85^{\circ} W/185^{\circ} < 75^{\circ}$ . There are spaces of 1 ~ 3 m between the rows and an extension of 10 ~ 20 m for the joints. The other is “tense joint” vertical to the strike of the bedrock with smooth-jointed surface that has an attitude of  $N 13^{\circ} W/77^{\circ} < 80^{\circ}$ . There are spaces of 0.8 ~ 2.5 m between the rows and an extension of 10 ~ 20 m for the joints.

The sliding rockmass (i.e., rockslide before failure) of The Jiweishan Hill was cut into “toy bricks stacked on the inclined soft cushion” by two sets of joints and a set of soft layers. There were karst caves, sinkholes, and voids with the maximum diameter of tens of meters, and additionally, yellow secondary argillaceous interlinings adhering to the western side that obviously decreased the strength of rockmass.

The mining activities in The Jiweishan Hill had existed since the 1920s. The mining area lies in the iron ore layer at depth, with a thickness of 0.96 ~ 1.35 m (the average thickness is 1.12 m). For a long time, the tunnel and gob areas have been excavated within an area of 50,000 m<sup>2</sup> which could affect the stress distribution and deformation on The Jiweishan Hill to some extent.

**Fig. 5** Overview of formation of the Jiweishan Hill (5 h before sliding)



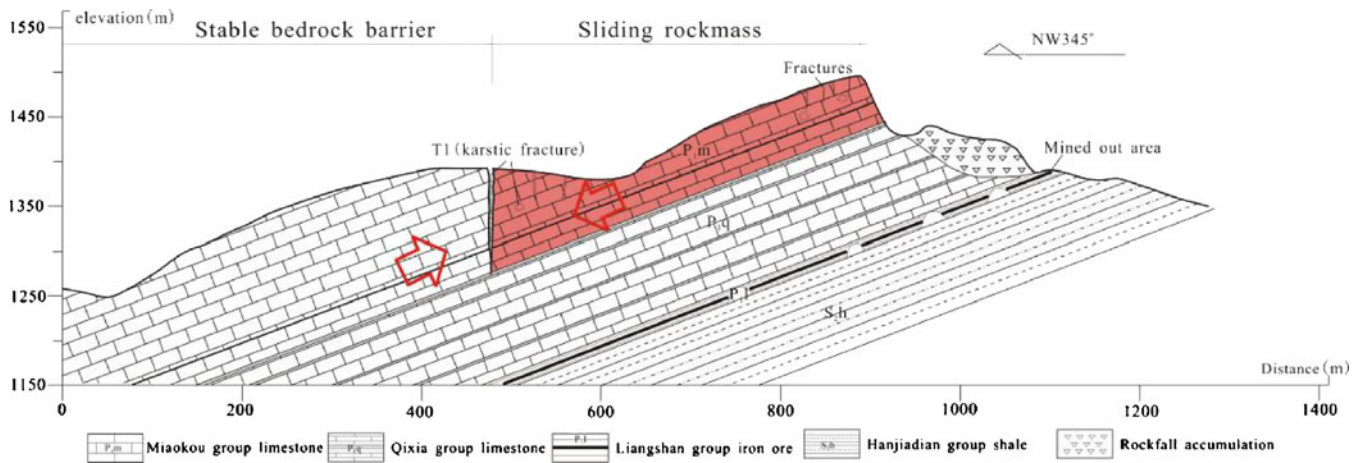
P,m- Limestone of Maokou Group; P,q3 Limestone of Upper Qixia Group; P,q2- Limestone of Middle Qixia Group; P,q1 Limestone of Lower Qixia Group; P,l- Ore bed of Liangshan Group; S,bj Sand shale of Hanjadian Group.

#### Rockmass structure and pre-slide conditions for the Jiweishan rockslide

##### Characteristics of separating planes

The sliding rockmass of Jiweishan Hill was separated from the parent bedrock by two wide karstified fractures containing small caves infilled with clay materials and a sliding plane: the rear boundary was Crack T0, the western boundary was Crack T1, and the bottom soft layer was located at R2 (Fig. 7).

- Crack T0. It occurred in a straight line along the EW-direction of the original tectonic plane with a length of 152 m and a depth of 60 ~ 70 m. A terrace was generated at the interface between P<sub>1</sub>m and P<sub>1</sub>q which shown an obvious long-term tensile process. The karstic erosion zone of the crack is about 2 m wide. It is inferred that the crack is over 10,000 years old because within, there are three dense karstic fissure belts that have developed.
- Crack T1. It occurred in a straight line along the NS-direction of the tectonic plane with a length of 530 m and a depth of



**Fig. 6** Profile map shown the relationship between the creeping of the sliding rockmass and the barrier of dipping stable bedrock along the true dip direction (downslope dipping; section location shown in Fig. 2)

60 m. The karstic erosion zone of the crack is about 2 m wide. Also, it is inferred that the crack is over 10,000 years old because it contains small sinkholes and karst caves. Due to the lateral slide of The Jiweishan rockslide, a chain of sinkholes with a dislocation of 0.5~1.5 m along T1 crack was formed under the unloading process and dozens of horizontal large scratches with reverse-steps occurred on the surface of the crack, and the large-sized indents can be seen at the lower part of the crack as a result of rockslide scraping.

- R2 soft layer. It was the bottom sliding plane for the rockslide. It was created by the long-period creep process of the interbedded stratum containing carbon and bitumen, and has a thickness of about 30~50 cm.

#### Characteristics of structure of sliding rockmass

The inclined bedding rockslide presents generally a “creeping-shearing” failure pattern controlled by soft layers. Huang (2007) divided this failure pattern of the slope into two sections: the

upper “driving area” (section I) and the toe “passive area” (section II). Under the gravity load, the rockmass in section I slide along a soft layer and the rockmass in section II is pressed and cut by a process of shearing stress. As the reduction of the shearing strength occurs, the sliding force is gradually increasing.

The Jiweishan rockslide had the same structure pattern. The sliding rockmass before it began to move was similar to the prismatic body with a maximum length of 720 m, a width of 152 m, a thickness of 60 m, and a volume of 5 million m<sup>3</sup>. The prismatic-body-shaped sliding rockmass could be divided into the rectangular-solid-shaped “driving block” and the triangular-prism-shaped “resisting key block” (Fig. 8).

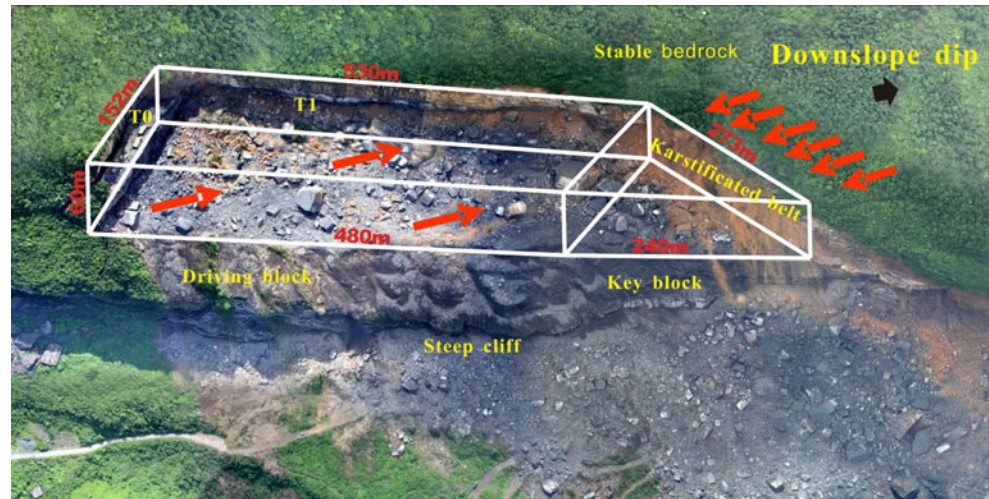
- Driving block. It had a plane shape of quasi-quadrilateral, with a length of 480 m, a maximum width of 152 m, an average width of 141 m, a thickness of 60 m, and a volume of 4.06 million m<sup>3</sup>. The block is made of Maokou limestone (P<sub>1,m</sub>) and Qixia limestone (P<sub>1,q</sub>). Its eastern and northern sides were intact, but the southern and the western were completely

**Fig. 7** Apparent sliding of the massive rock slope along inclined bedding slope





**Fig. 8** Geological model of the sliding mass of the Jiweishan rockslide (before exiting)



separated by crack T<sub>0</sub> and T<sub>1</sub>, and the bottom was discontinued by the R<sub>2</sub> soft layer.

- Resisting key block. This block had a plane shape of a triangle, with a length of 240 m, a width of 130 m, a thickness of 60 m, and a volume of 0.94 million m<sup>3</sup>. This block was made of Maokou limestone (P<sub>1m</sub>) and Qixia (P<sub>1q</sub>) limestone. Its northeastern side was intact and the bottom was separated by R<sub>2</sub> soft layer.

The resisting key block and the lateral stable bedrock were not separated thoroughly due to the fact that Crack T<sub>1</sub> gradually faded away towards the north and turned towards the karstified zone with a direction of N 21° E from north and a length of 273 m where the vertical karst pipes, sink holes, and fissures were located. The maximum diameter of the karst pipes was over 3 m and the voids were filled with brown-yellow residual clay. An accumulated width of karst pipes was about 165 m that indicated the ratio of the solution space length (165 m) and total length of the karstified zone (273 m) in horizontal was over 60%, i.e., only 40% limestone remained to be connected (Fig. 9).

The key block obstructed from the driving block through the following two manners: (1) a lateral shearing resistance supplied

by the remained 40% brittle limestone rockmass with an accumulated length of 108 m and (2) a bottom sliding resistance along the R<sub>2</sub> soft layer.

#### Pre-slide conditions for the Jiweishan rockslide

Since 1994, the Jiweishan Hill has been listed as a geohazards risk zone of by local county government, and the village-based regular and simple observation has been undertaken.

Before 2005, the previous site of the village within the geohazard risk zone was relocated to the new safe site. The village had a population of 900.

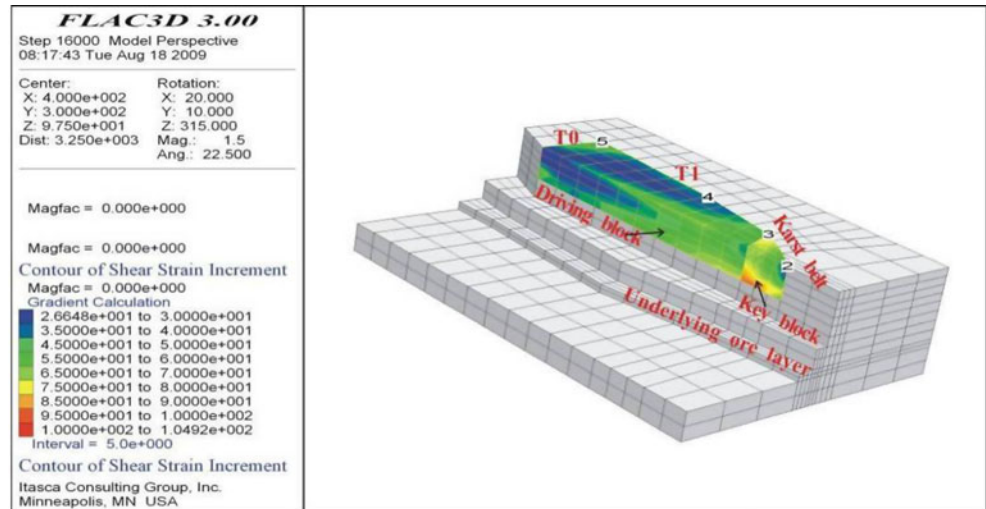
In 2007, the special geological investigation on the Jiweishan Hill was conducted since the heavy rainfall. The result of the renewed investigation is almost the same as before, but the mining area had not been encompassed inside of the risk zone.

In the morning of the June 2, 3 days before sliding, Mr. Re Guangmu, a monitoring person, watched the 1,000 m<sup>3</sup>-volume rockfall of as it occurred near the front of the rockmass, i.e., the key block, and continued watching as the slide stopped abruptly in the road, which was where the evacuated village had been located within the risk zone.

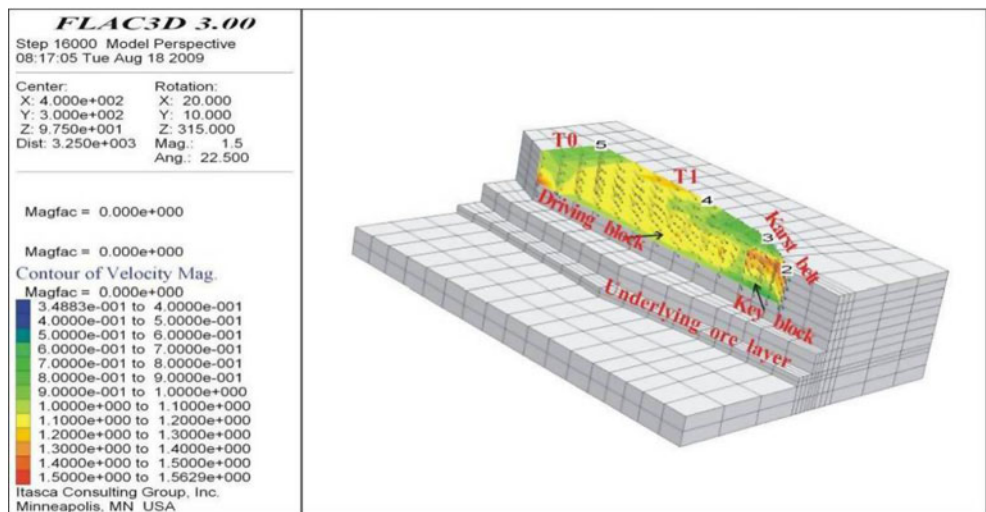
**Fig. 9** Karstified zone and brittle rupture surface at the side of key block (remanted after sliding)



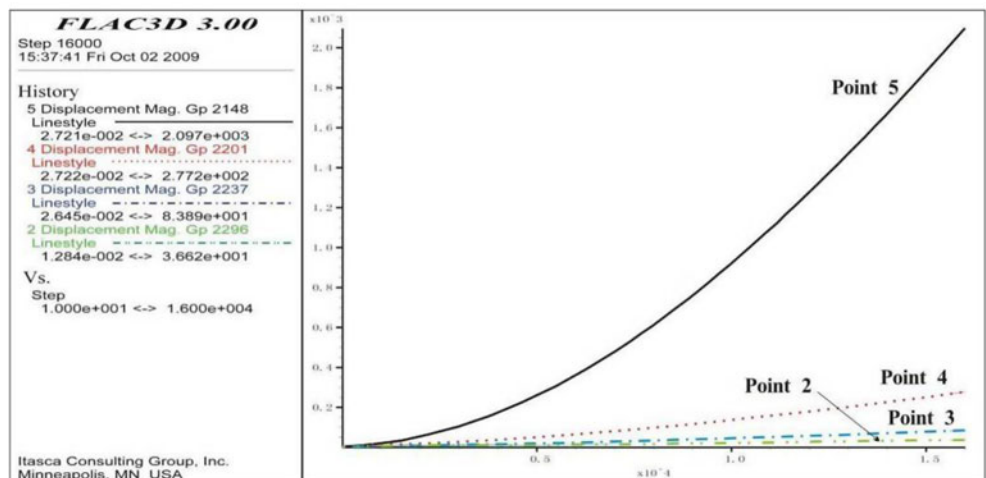
**Fig. 10 a–c** Simulation results of shear strain increment and velocity under nature condition



**(a)** Contour of shear strain increment

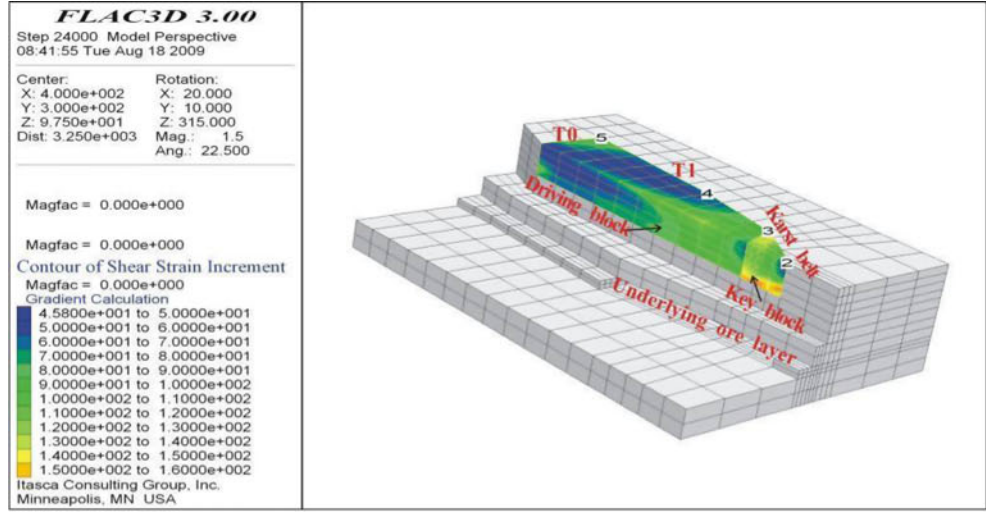


**(b)** Contour of velocity magnitude (mm/s)

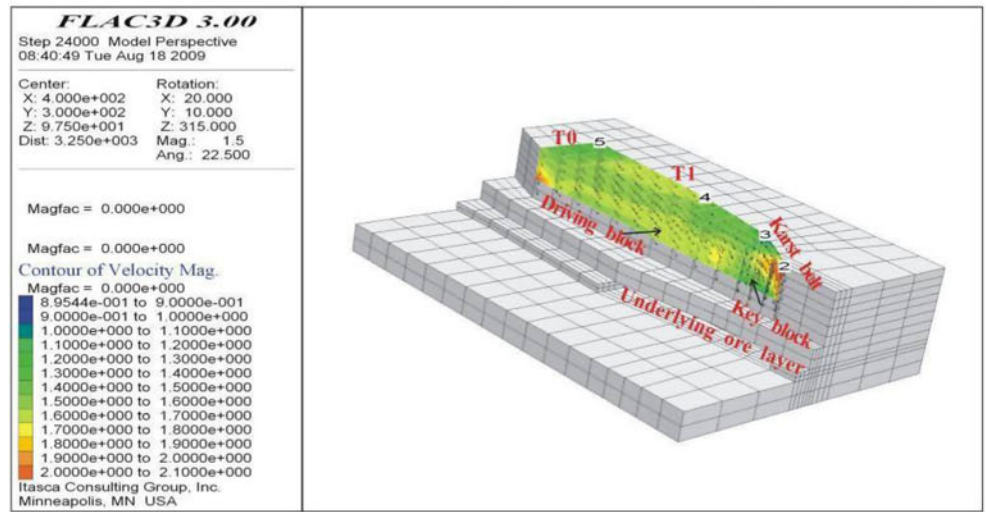


**(c)** Displacement for points 2, 3, 4 and 5 (mm)

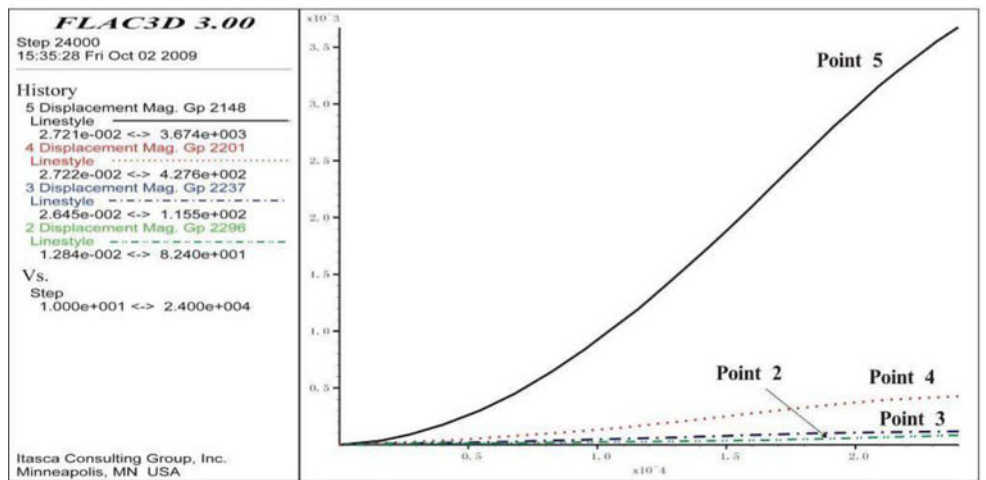
Fig. 11 a–c Simulation results of shear strain increment and velocity under mining condition



(a) Contour of shear strain increment



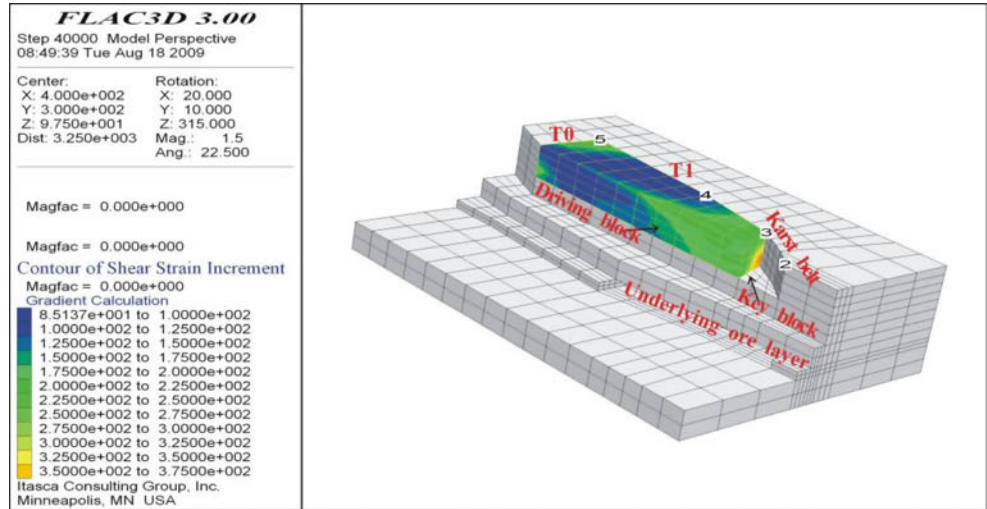
(b) Contour of velocity magnitude (mm/s)



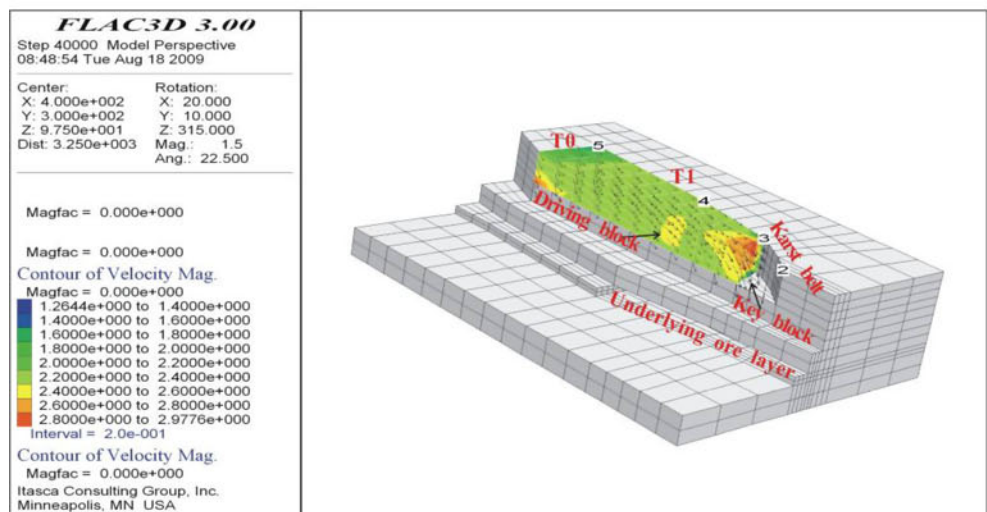
(c) Displacement for points 2, 3, 4 and 5 (mm)



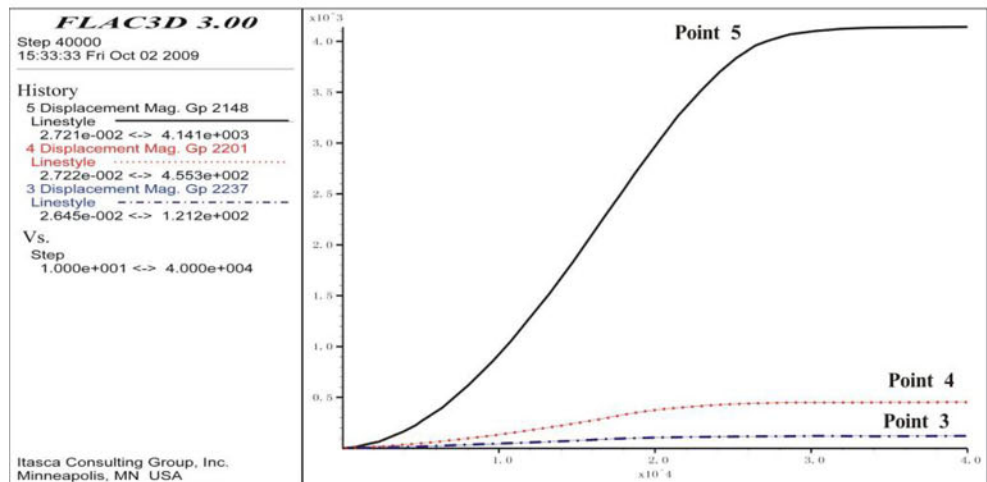
**Fig. 12 a–c** Simulation results of shear strain increment and velocity under key block sudden failure condition



**(a)** Contour of shear strain increment



**(b)** Contour of velocity magnitude (mm/s)



**(c)** Displacement for points 3, 4 and 5 (mm)

**Table 2** Physical and mechanic parameters for the Jiweishan rockslide

No.	Rock type	$\rho$ (kN/m <sup>3</sup> )	$\Phi$ (°)	C (kPa)	$\gamma$	G (MPa)	K (MPa)
1	Maokou limestone	26	25~30	200~500	0.24	100	200
2	Qixia limestone	26	25~30	200~500	0.24	100	200
3	Sliding mass	26	20~25	100~300	0.24	100	200
4	Key block	20	20~25	100	0.24	100	200
5	Mining bed	15	22	45	0.15	50	200

In the morning of the June 4, a day before sliding, rockfall occurred again with a volume of about 3,000 m<sup>3</sup> in the front of the key block.

At about 9 a.m. of June 5, 6 h before main slide, local governors and monitoring persons went to the risk site, looked around in front of the key block and took three quick actions: they set up a warning boundary to stop anyone from entering the area, closed the road, and increased the monitoring frequency.

No one knew at that time that there would be a rapid long runout catastrophic rockslide instead of a short small rockfall, which is what was expected.

#### Simulation of the failure processes for the Jiweishan rockslide

The finite element method, discrete element code and finite difference method have become powerful tools for simulating slope failure. In this paper, the failure processes of the Jiweishan rockslide are analyzed with the assistance of the modeling software, FLAC<sup>3D</sup> (Griffith and Lane 1999; Itasca Consulting Group Inc 2005). The sliding rockmass of the Jiweishan rockslide could be analyzed by equivalent continuum approach while the fractured blocks are equably distributed. FLAC<sup>3D</sup> is applied since that is an explicit finite difference program to study numerically the mechanical behavior of a continuous three-dimensional medium as it reaches equilibrium or steady plastic flow. In FLAC<sup>3D</sup>, the general dissection of the four bedding rockmasses, two cracks, and one karstified zone into zones is performed. Each zone is dissected automatically by the code into sets of tetrahedral groups.

FLAC<sup>3D</sup> also provides a description of large-strain deformation, involving large displacements, displacement gradients, and rotations of the key block and the bedrock collapse at the margin. None of the boundary conditions of the problem consisted of surface tractions, concentrated loads and displacements, body forces and initial stress conditions that are imposed as given. But, a null material is used to represent the iron ore material that is excavated at the bottom and the key block material that is removed from the failure at first. The stresses within a null zone are automatically set to zero. The two cracks and the karstified

zone are regarded as interface elements that are characterized by Coulomb sliding and/or tensile and shear bonding. Interfaces have the properties of friction, cohesion, dilation, normal and shear stiffness, tensile, and shear bond strength.

#### Modeling of the Jiweishan rockslide

By using FLAC<sup>3D</sup>, the natural evolution condition, the mine-disturbed condition, the key block failure condition and the large deformation sliding condition are discussed, and four observation points 2#, 3#, 4#, and 5# are established at the western edge of the sliding mass so as to analyze the displacement for different parts. Figures 10, 11, 12, and 14 show the simulation results under various conditions.

The Mohr-Coulomb yield criterion is adopted to simulate the sliding of the rockmass. Because a non-specialized test was conducted for emergency work, some of the physical and mechanic parameters for the Jiweishan Hill rockslide of are produced by a combination of analogy and back analysis. Many parameters were cited by using studies of the similar Lianziya unstable rockmass of the Three Gorges area (Yin, 1994). The parameter values for the driving block, resisting key block, separated planes (including sliding plane), and bedrock are given in Tables 2 and 3. A null material model is also used to represent tunnels and gob areas that were excavated due to mining at the bottom.

#### Simulation under a natural condition

The rockmass creep is simulated along the R2 soft layer with the attitude of N 15° W <21~35° under natural conditions. According to the study on shear strength of the Lianziya unstable rockmass, the peak friction angle for the soft layer is about 30.1°, and the cohesive strength is 280 kPa. Figure 10a indicates the maximum shear strain increment occurs at the bottom sliding surface of the key block, with a value of 100~105, and the maximum value zone of velocity nephogram appears on the top of the key block and at the bottom of the sliding mass adjacent to crack T<sub>0</sub>, with the maximum velocity of 1.50~1.56 mm/s. Figure 10b shows that the

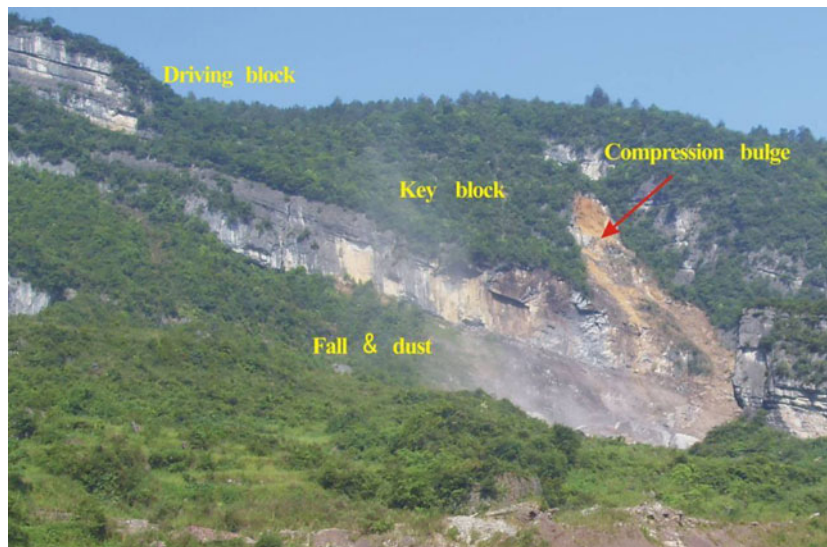
**Table 3** Physical and mechanic parameters for soft layers of the Jiweishan rockslide

No.	Soft-layer type	$\Phi$ (°)	C (kPa)	$K_n$ (MPa/m)	$K_s$ (MPa/m)
1	Crack T <sub>0</sub>	8	0	100	10
2	Crack T <sub>1</sub>	8	20	1,500	10
3	Karst belt	20	50	2,500	100
4	Sliding surface	20	200	2,000	50

$\rho$  is bulk density,  $\Phi$  is friction angle,  $c$  is cohesive strength,  $\gamma$  is Poisson's ratio,  $K_n$  is normal stiffness,  $K_s$  is shear stiffness



**Fig. 13** Front bulge and fall of resisting key block (5 h before sliding)



displacement direction is changed from N 15° W to NNE–NE. From Fig. 10c, we can see that the displacements of points 2#, 3#, 4#, and 5# are 10, 25, 100, and 600 mm, respectively, and it shows that displacement of the rear mass (point 5#) amounts to 60 times more than the one in the front part of the mass (point 2#). The displacement result indicates that the rear block is driving and the front block is resisting.

#### Simulation under mining condition

The mining activity has been in operation since the 1920s at the bottom of the cliff. The thickness of the iron ore layer varies between 0.96 and 1.35 m and the mean thickness is 1.12 m. The mined-out area of the gobs, and tunnels has been excavated within an area of 50,000 m<sup>2</sup> (Fig. 2)

The method of backward, retreat mining was applied with the mining rate of 85% and the roof was supported by the room and pillar system. Mr. Jiang Wenfu, a mineworker from 1969 to 1995, told us that the iron ore was over-mined in 1958 and the deformation of the railway occurred in the #5 adit and some rockfall happened nearby. Since then, the mining activity has been stopped. The #3 adit collapsed before 1969. The #4 adit has been stopped since 1985 and is stable. The #2 adit was mined from 1989 to 1990 and is stable. The #1 adit had been mined and also is stable. Three days before sliding when the local rockfall occurred, a special inspection group went into the #1 adit and found that room-pillars, tunnels, and roofs were not obviously damaged.

The disturbance on stress and deformation of the rockmass is simulated under long-term mining condition for iron ore underneath the cliff. According to the characteristics of FLAC<sup>3D</sup>, the mined-out area, i.e., tunnel and gob, is setup by a null material model. The maximum shear strain increment is still located at the bottom sliding surface of the key block, but the value is increased to 150~160 (Fig. 11a); the maximum velocity on the top of the key block and at the bottom of the sliding mass adjacent to crack T<sub>0</sub> is enhanced to 2.00~2.10 mm/s. The general displacement direction is NNE–NE (Fig. 11b). However, compared to that in a natural condition, the downward displacement component is increased greatly, and at the front edge of the key block especially, the downward displacement vector is nearly vertical, which indicates

the failure character. Figure 11c shows that the displacements of points #2, #3, #4, and #5 are 50, 100, 450, and 3,600 mm, respectively, indicating that the displacement of the rear mass (point #5) amounts to 72 times the one in the front mass (point #2). Similarly, the displacement result indicates that the rear block is driving and the front block is resisting. Compared with the one in the natural condition, the displacement at the driving block is increased from 600 to 3,600 mm, but the displacement at the resisting key block is not obvious. Therefore, we can conclude that the sliding force of the driving block is increasing step by step, and the strain energy of the key block is accumulating gradually.

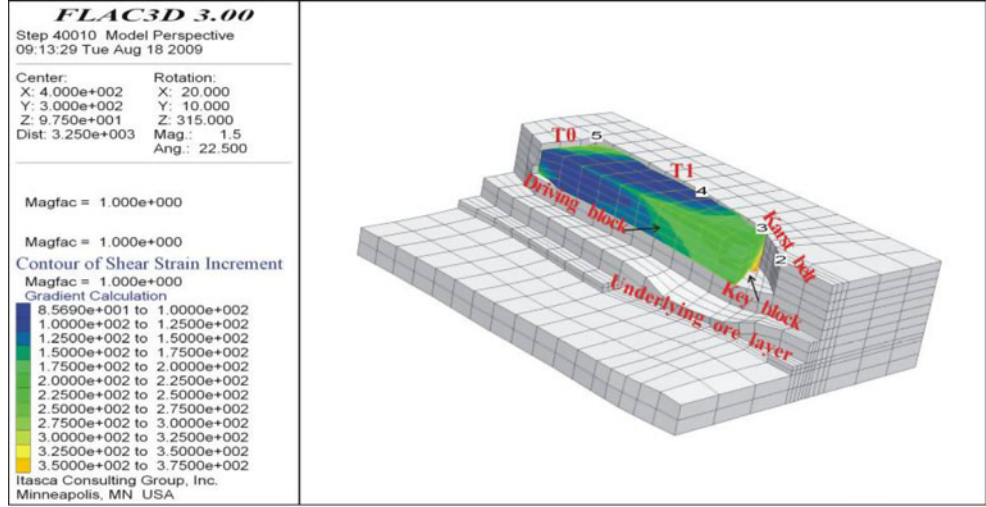
#### Simulation under the instantaneous failure condition of the key block

The deformation and translational slide of the driving block with a volume of 4.8 million m<sup>3</sup> is simulated assuming the instantaneous brittle failure of the resistant key block along the karstified zone due to the overwhelming driving force from the back. The key block falls suddenly and the front edge of the driving block loses its support (Fig. 12a). The simulation shows that the maximum shear strain increment zone is generated at the front edge of crack T<sub>1</sub>, with the value of 350~375 and the distinct high-velocity zone appears at the front edge of the driving block, with the value of 2.80~2.98 mm/s. The sliding direction for the driving block mass is mainly NNE and the vertical displacement is obscure (Fig. 12b). The displacements for points #3, #4, and #5, with the value of 200, 480, and 4,500 mm, respectively, that show displacement at the rear of the driving block (point #5) amounts to 25 times greater than the one in the front of the driving block (point #3; Fig. 12c). The simulated result of displacement also indicates that the rear block is exerting force. Field investigation indicates that, a few days before the occurrence of The Jiweishan rockslide–rock avalanche, obvious compression bulges and local falls with thousands of cubic meters in volume were generated in the key block. The simulation result above is seems to closely coincide with the real situation (Fig. 13).

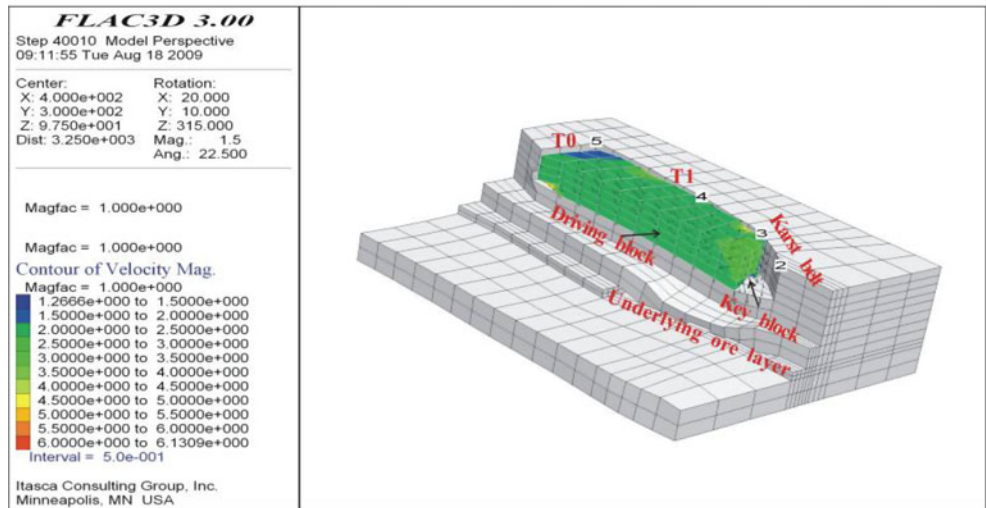
#### Simulation under the large deformation sliding condition

Without the support by the resisting key block, the driving block with a volume of 4.8 million m<sup>3</sup> rapidly slid and it dragged the

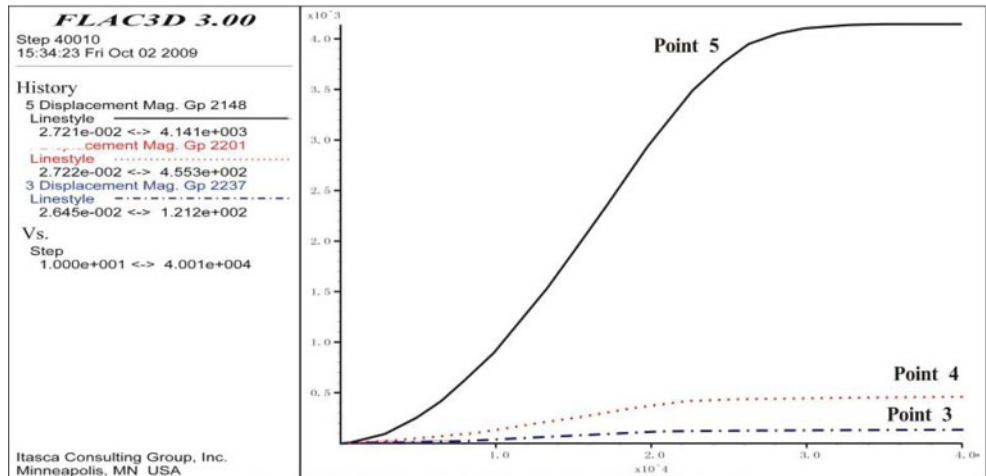
Fig. 14 a–c Simulation results of shear strain increment and velocity under large sliding condition



(a) Contour of shear strain increment



(b) Contour of velocity magnitude (mm/s)



(c) Displacement for points 3, 4 and 5 (mm)



**Table 4** 2D factor of safety under lateral resisting slide of the Jiweishan rockslide (without R2 softlayer)

State		Shear strength of sliding belt		FOS	Note
		$\Phi$ (°)	C (kPa)		
Initial state	Sliding block	35	150	1.71	Peak strength
	Key block	35	200		
Creep state	Sliding block	23	100	1.13	2/3 peak strength
	Key block	23	140		
Critical state	Sliding block	23	100	0.96	1/3 peak strength
	Key block	13	70		
Failure state	Sliding block	23	100	0.15	Key block is null model
	Key block	0	0		

bottom bedrock at the margin due to its weight and mass and force of collision. The rockmass of the driving block disintegrated rapidly and fell from the perch of the cliff due to the open front edge (Fig. 14a). The shear strain increment is still 350~370 and it is unclear as to whether it changed, and meanwhile, and the cloud contour of velocity is not obviously changed as indicated in the simulation of FLAC<sup>3D</sup>. Figure 14b shows that the displacement direction is dominantly NNE along the sliding plane and the downward displacement is obvious. The field investigations show that the bottom bedrock between the sliding plane and the mined-out zone at the margin had collapsed, which coincides with the simulation result (see also in Fig. 8).

**2D analysis for factor of safety under a lateral resisting slide**

For an oblique inclined bedding rockslide, the lateral discontinuity plane is very important to allow for the change in the sliding direction from true dip to apparent dip. The above simulation results clearly indicate the sliding characteristic along crack T1 and the shearing characteristic along the karstified zone between the key block and the lateral stable bedrock. In order to further study the slide-resistant characteristic of the lateral discontinuity plane and the apparent movement of the sliding rockmass under the lateral bedrock barrier, a simplified plane model is analyzed by using the strength reduction method of FLAC<sup>3D</sup> provides a given in that the control processing of the R2 soft layer is the same on the whole rockmass. Thus the factor of safety (FOS) along crack T1 and the karstified zone can be computed. Similarly, gravity acceleration acted on the lateral crack T1 and karstified zone should be decomposed. If the given dip angle of the soft layer is 30°, then the component acceleration ( $g_h$ ) on the crack T1, and the karstified zone should be 0.5g, i.e.,  $g_h = g \times \sin 30^\circ = 0.5g$ .

Generally, the slope failure is identified as having the failure shear strain develop from the toe to the top of the slope by reducing the value of c and  $\Phi$  gradually until the slope failure occurs, and the corresponding reduction factor is defined as the factor of safety (Matsui and San 1992; Dawson et al. 1999; Zhao et al. 2002). The user’s guide of FLAC<sup>3D</sup> software specified that the “strength reduction technique” is typically applied in factor-of-safety calculations by progressively reducing the shear strength of the material in order to bring the slope to a state of limiting equilibrium (Itasca

Consulting Group Inc 2005). The safety factor FOS is defined according to the equations:

$$\Phi_r = \arctan(\tan\Phi/FOS) \tag{1}$$

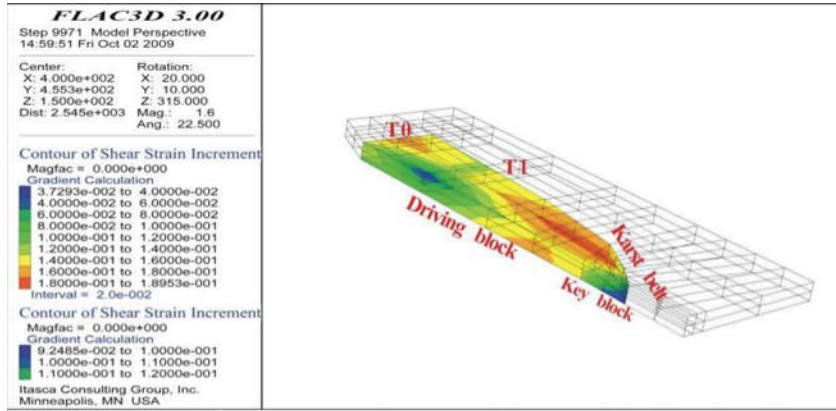
$$c_r = c/FOS \tag{2}$$

The computed results for FOS under the same four conditions as the above 3D simulation are: the natural evolution condition, the mining-disturbed condition, the key block failure condition, and the large deformation sliding condition, and are listed in Table 4. This represents the resistant sliding processing of the crack T1 and the key block on the rockslide. When the key block failure instantaneously occurs, the sliding direction is deflected to NE and the anti-sliding force is almost zero (Fig. 15 and Table 4). It is worth pointing out that the computed FOS factor for the rockslide here could not be represented as the conventional FOS due to the missing of slide-resistant force on the bottom sliding plane in which the component acceleration ( $g_v$ ) on the bottom soft layer should be 0.866g, i.e.,  $g_v = g \times \sin 60^\circ = 0.866g$ .

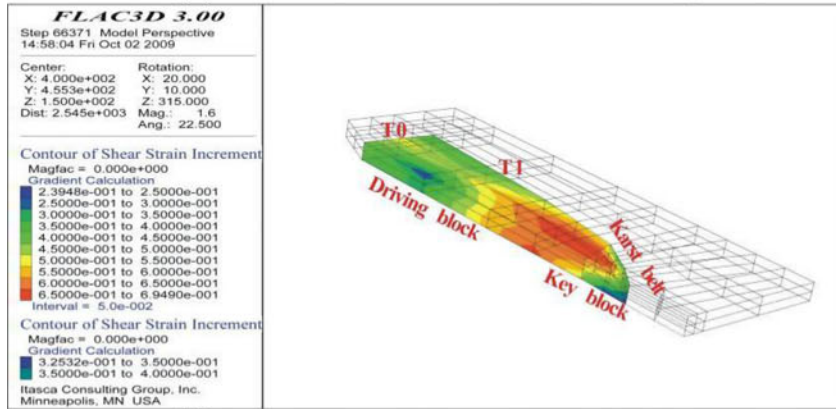
**Rapid long runout movement of rockslide–rock avalanche**

It was not imagined or taken into account that a rapid long runout catastrophic rockslide–rock avalanche could occur at the Jiweishan Hill, or even in the Chongqing area. The overview of the Jiweishan rockslide accumulation looks like an oblique long horn, with a length of 2,170 m, a maximum width of 470 m, a covered area of 0.47 million m<sup>2</sup> and a volume of about 7 million m<sup>3</sup>. The volume of the accumulation is 1.4 times the volume of the original rockmass of the rockslide, that was about 5 million m<sup>3</sup>, i.e., the enlarged index (Ie) is about 1.4 (Ie=volume of accumulation/volume of original rockmass). The accumulation can be divided into four zones: the main rockslide accumulation zone, the rock avalanche (fragment flow) accumulation zone, the rockslide scraping zone and the scattering zone (Figs. 16 and 17). The initial break up of a mass of falling or sliding rock occurs by the opening up of pre-existing joints and other discontinuities to form an assortment of blocks. As their speed picks up,

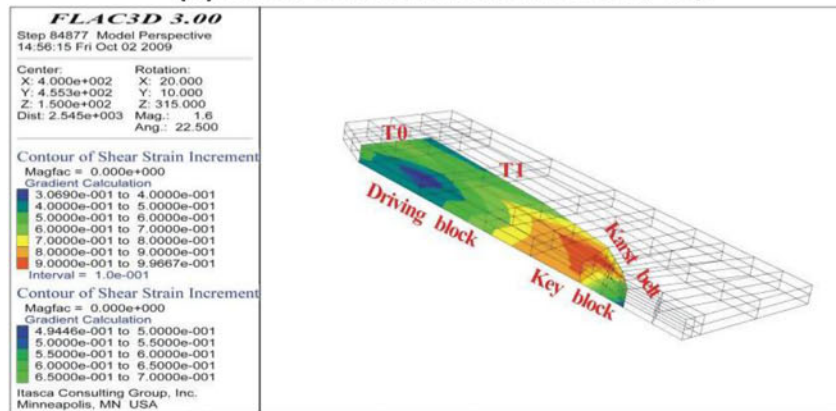
Fig. 15 a–d Simulation results of shear strain increment under 2D lateral sliding condition



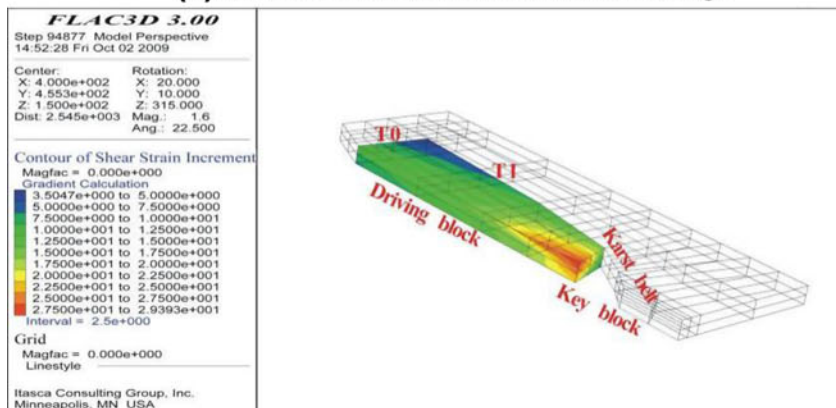
(a) Contour of shear strain increment at initial stage



(b) Contour of shear strain increment at creep stage

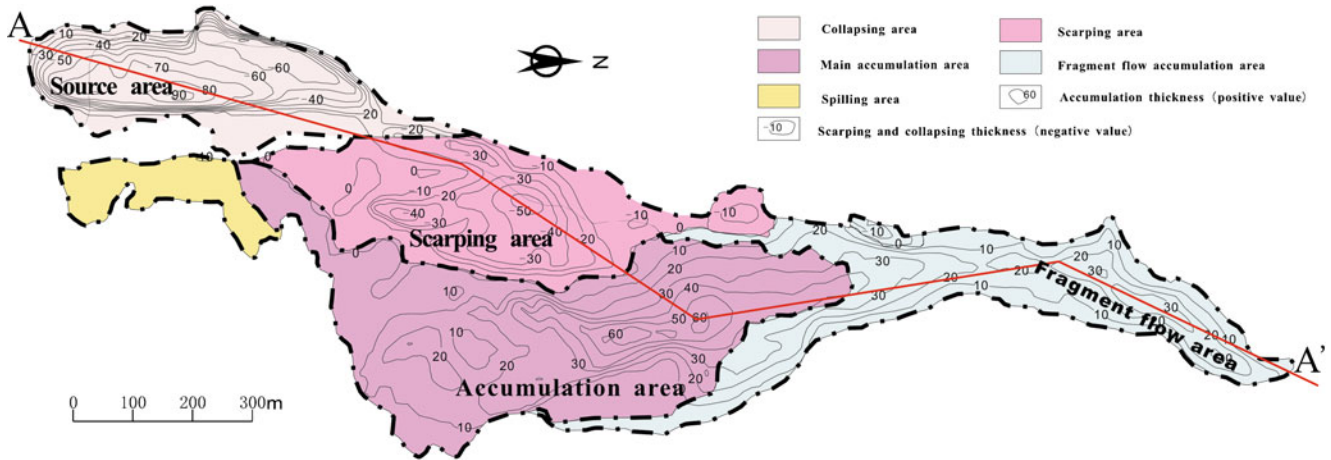


(c) Contour of shear strain increment at critical stage



(d) Contour of shear strain increment at failure stage





**Fig. 16** Layout map of thickness contour of the Jiweishan rockslide–rock avalanche (fragment flow)

collisions between these blocks and between them and the substrate will occur and they will begin to shatter (Hutchinson 2006).

- The main rockslide accumulation zone. This zone occurs in the NE valley with an average thickness of 30~40 m, a maximum thickness of 60 m, a length of 800 m, and a maximum width of 470 m. It was generated by the direct deposit of a high-speed sliding mass at an elevated position when it terminated. It is mainly composed of stone blocks of P<sub>1</sub>q and P<sub>1</sub>m limestone, with a maximum long-axis length of 30 m and a volume over 15,000 m<sup>3</sup>. The huge blocks were strongly karstified, which showed the weak characteristics and the active groundwater acting on the rockmass before failure. The rapid runout sliding mass violently crashed into the opposite side of the valley about 500 m away from the area that caused the following three effects: huge blocks were disintegrated and smashed and as a result provided abundant material for a long runout rock avalanche (fragment flow), the opposite slope was scraped, inducing some rock-falls and rockslides, and the vegetation was destroyed by an air blast.
- The rock avalanche (fragment flow) accumulation zone. After the collision, the broken sliding mass turned into a fragment

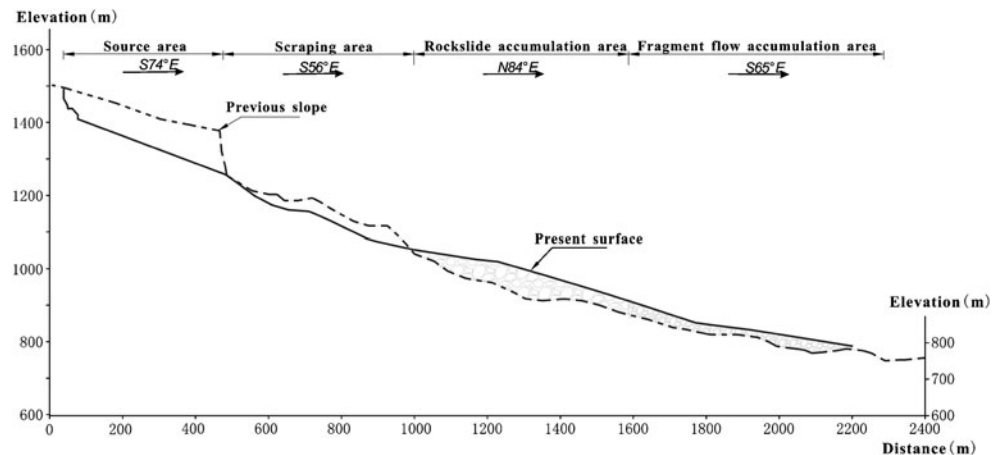
flow and continued moving with high speed. With the energy dissipation, large blocks stopped at the main accumulation zone gradually, but the sliding materials with relatively small grain size continued moving ahead, causing the formation of the rock avalanche accumulation area with an obvious streamlined characteristic.

- The rockslide scarping zone. During the process of rapid rubout of the sliding mass, the convex isolated hill at the right side was stripped away. Meanwhile, a NE-strike hill lying at the front edge of the shear terminal area was carried into the rockslide accumulation zone. Because of this added supplement of the scraped rockmass, the actual accumulation volume should be larger than that of the rockmass in the accumulation area.
- The scattering zone. This zone was mainly located east of the source area, predominantly consisted of isolated large stones and overspreading broken stones and fragments, with a thinner accumulation thickness. Influenced by the powerful airflow during rapid sliding, the vegetations in this area was blown down and flattened, with directional array.

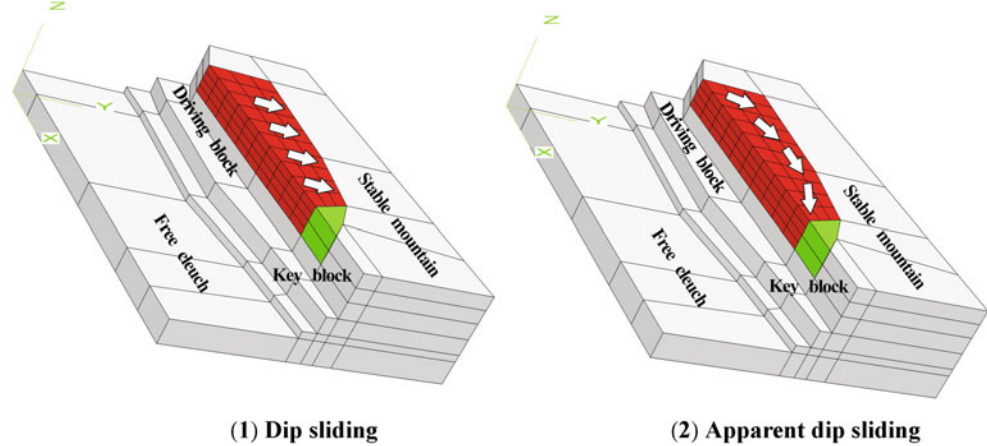
#### Discussion on the mechanism of apparent dip sliding

Based on the above analysis, it can be concluded that the failure mechanism of the apparent dip sliding of the Jiweishan rockslide

**Fig. 17** Profile map of the Jiweishan rockslide–rock avalanche (fragment flow)



**Fig. 18** Conceptual models of apparent dip sliding of oblique inclined bedding rockslide



is as follows: first, the thick-bedded limestone was split into “toy bricks” by two sets of joints and the bedding composed of carbon soft layers; second, the sliding force of the driving block was gradually increasing while the shear strength was decreasing due to the inclined rockmass which crept towards a true dip of NNW; third, due to the barrier of stable bedrock, the driving block deflected into an apparent dip of NNE and destabilized the northern supporting rockmass, which is the resisting key block; finally, the key block failed instantaneously both for the reasons of the increase of shear stress from the driving block and the reduction of strength and stiffness of the key block under the long-term karstic processes and mining disturbance.

Noteworthy is that the thick-layered structure of the rockmass and the key block to resist are factors that are necessary to be in place, for this event. In fact, for the thin layer structure “toy bricks”, successive lateral fall and topple is easier, and if no key block exists to resist, the sudden large-scale rockslide, it is improbable that such a large rockslide would occur, and instead the expected occurrence of the small-scale translational rockslide and rockfall would take place, due to the excessive separation of the rockmass and the suitable inclining angle of the soft layer.

Hungr and Evans (2004) identifies a translational rock block or wedge slide (Type C) of massive rock slope failure and proposes that a simple translational sliding failure results where major weakness planes exist, dipping at or near to the slope direction. The weakness plane may be a weak direction in an anisotropic rock mass and other two planes may combine to form a wedge failure. The cases of the massive rock slope failure are common in moderately folded sedimentary rocks, particularly carbonates. Many similar cases have been researched in China. Prof. Liu et al. (1995) put forth the concept of “apparent sliding force” by studying the failure mode of Lianziya unstable rockmass, in the Three Gorges area; Dr. Chai et al. (2009) proposed the “toy bricks” factor for slope deformation under control of a rockmass structure; Prof. Shi (2006) advanced the method of considering joint polygons, cutting joint blocks, and finding key blocks for a generally open surface.

Therefore, based on aspects of this research cited above, the following five conditions must exist for the apparent dip sliding of an inclined bedding rockslide (Fig. 18).

- A block-fracture bedding structure. The rockmass is split into obvious distinct blocks with several groups of joints, similar to

“toy bricks” and is separated from the bedrock with at least three sets of large boundary cutoff features, such as, large joint, fault, and a soft layer. The structure of force mechanisms of the “toy bricks” will evolve from a network to a tree configuration, and then to a line shape due to the unbalanced movement. This indicates that the stability of the rockmass is decreased step by step.

- An inclined rockmass barrier. The sliding rockmass along the dip angle is barricaded or blocked, by the inclined stable rockmass and then the sliding direction is deflected from a true dip angle to an apparent dip angle.
- An apparent dip-related progression of the slide. An open space, such as, valley and cliff, exists for the sliding rockmass to progress along an apparent dip. The results of the FLAC3D simulation shows that the driving block movement is toward the North along Crack T<sub>1</sub>, but the direction changes and turns toward the Northeast near the open space especially, and downward movement is predominant after the failure of the key block.
- The driving block sliding. The “toy bricks” rockmass movement is a long-term creeping that reduces the shear strength along the bottom soft layer from peak to residual value, and accordingly, increases the sliding force.
- The key block resistance and brittle failure. The pressure on the key block is increased by the driving block and the strength of the key block is reduced due to karstification, rainfall, and mining. The brittle failure of the karstified zone between the key block and the lateral stable bedrock occurs instantaneously and are the major factors responsible for generating the catastrophic rockslide-rock avalanche (fragment flow).

### Conclusions

Taking the Jiweishan Hill as an example, a new failure pattern for inclined thick bedding rockslide-rock avalanche (fragment flow) is studied and introduced here, by analyzing the geological structure, and the destabilizing iron ore excavation factor. The failure pattern was then simulated by using the software FLAC<sup>3D</sup>. The result reveals that the five basic conditions exist for apparent dip sliding of an inclined bedding rockslide. It is important to model the triggering mechanism of the instantaneous failure of the rockmass, and model both physical properties, those being that the sliding force is increased by the driving rockmass and the fact that the strength of the key block is decreased. It is worth noting that the mining activity associated with the iron ore layer

(with a thickness of 2~5 m, at 100 m underneath the sliding plane,) must be given further consideration as the mechanism of the mining-related trigger, and must be further studied.

As a result of the knowledge gained through field analysis and modeling for this rockfall, raising awareness about these conditions through education and a possible warning 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 given consideration by local government and/or community decision-makers.

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