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Research Article

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Study on instability criteria of toppling-sliding collapse

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ABSTRACT

Toppling type collapse is one of the majormodels of collapse disasters and usually occurs in the slope with weak layer in the lower part of the hard rock. When the weak layer in the lower part of the slope is affected by the external environment and human engineering activities, tensional cracks will occur and the slope incline outward. There are different failure modes in the topping process because of the diversity of geological structures, and toppling-sliding failure is a common mode of toppling type collapses. According to the stress-strain relation of rock, collapse body can be seen as a rigid body. This paper presents the warning model of fracture width with respect to the consistence of the upper and lower rotation angles of rigid body. Moreover, this warning model has been validated by the two-dimensional and three-dimensional numerical models, and the results of the warning model are between the upper and lower measuring values. It can be concluded that the curve shapes of rotation angles of model are consistent with the variation of the rotation angles of collapse body.

Key words: weak -layer; criteria for evaluating stability; toppling-sliding failure; numerical modeling

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INTRODUCTION

Collapses usually occur in the steep slopes with slope gradient greater than 50° and height more than 30 meters. The damage caused by collapses is sharp, shortand strong. Collapse disasters have recently received much attention, because of the huge personnel and property losses they bring about. Collapse research mainly focuses on the failure modes, failure mechanisms and stability (Hu, 1985; Wang et al., 2013; Cheng et al., 2005). In recent years, prediction and warning of collapseshasgradually becomea highly debated topic

Chen et al. (2006) postulated the chained evolution of falling collapses.Tianet al.(2009) usedthe gray catastrophe theory and acoustic emission to predict collapseinstability. Based on thecantilever beam theory, Tang et al. (2010) predicted the time of rock collapse ofthe falling collapse sequences on the escarpmentswith soft foundation.

U.GLAWE and P.ZIKA (1993) presented a forecast of the time of failure of a toppling rock tower failure on a slope edge, based on an extensive field study and on the long-term monitoring of the kinematics. These studies suggest that prediction and warning of collapsesisdifferent to thoseof landslides, due to the abruptnessof collapses and the diversity of damages they bring about. Therefore, establishment of the warning models should correspond to the failuremodes of different types of collapses.

However, toppling type collapse is poorly understood due to the diversity and complexity of its failure modes and other reasons, therefore it is necessary to consider multiple factors in the study. Given the geological and topographic diversities, the failure modes of toppling type collapses are quite varied. Toppling-sliding failure is a common mode of toppling type collapses. Based on the failure modes of toppling-sliding collapses, this paper presents a warning model of the failures of toppling-sliding collapses.

2. Failure mechanism

2.1 Failure mode

Toppling type collapse is characterized by steep slopes, soft-hard rock masses and nearly horizontal or inclined rock layers. The upper rocks are generally thicker,presentinga "hard topand soft bottom" look. Whenmultiplelayers of soft rocksexistin the hard rock mass, ladder hill slopes take shape as a form oftopography, such as the K400 collapse body in the Baocheng line, Qingchuan County, Sichuan Province, the landslide in Dongkagula, Shijing Village, Fenggang County, Guizhou Province, and the collapse body in Luolu Village, Shanpen Town, Zuiyi County, Guizhou Province, and so on.

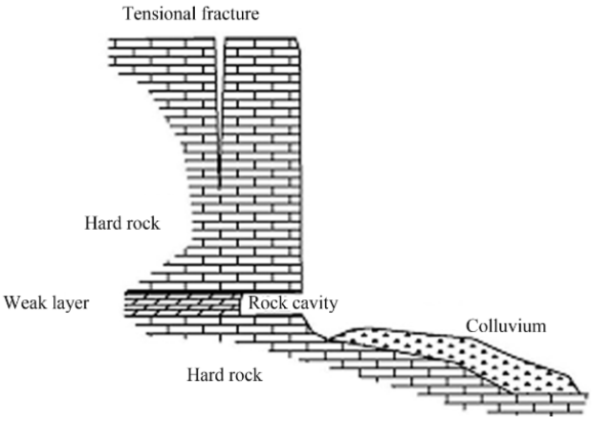

Fig. 1: Sketch of collapse by reason of mid-thick hard rock inter-bedded by thin weak layer

Toppling type collapse is one of the basic failuremodels of collapse disasters. There are two main causes of toppling type collapses, which are external environmental factors (river erosion, differential weathering etc.) and human engineering activities (mining etc.). Resulted from by either of the causes, toppling type collapses share basically the same failure mechanism. Rock cavities are formed in the lower part of the slope when it is disturbed, creating space for slope to sink by gravity. Consequently, tensional stress concentrates in the upper part of the slope. When there is enough sinking space in the lower part of the side slope and the tensional stress is beyond the tensile strength of rock mass, rock masses broke and tensional fractures take shape. The size of the deformation space in the lower part is linked to the growth of tensional fractures in the upper part.

2.2 Stress deformation analysis

Rock cavities occur in the collapse body because of external environmental factors in the lower weak interlayers (river erosion, water scouring, etc.) or human engineering activities. In this case, the barycenter of the interlayers in the collapse body bottom will inward transfer (Fig. 2), and the pressure will redistribute in the upper interlayers. Based on Saint Venant's principle, the difference between the effects of two different but statically equivalent loads becomes very small at sufficiently large distances from load; the weak interlayer below the collapse can be approximately seen as an affected zone. In the internal boundary of the affected zone, which is in the lower part of the tensional fracture, the pressure is considered to be similar tothe backpressure. Therefore, the pressure inthe weak interlayers can beapproximatelyassumed to be distributed in a ladder shape.

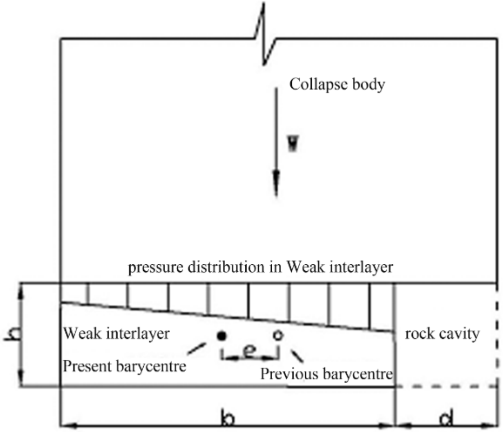

Fig. 2: Weak interlayer pressure distribution

Internal boundary pressure is:

$$p_1 = \gamma H(1)$$

External boundary pressure is:

$$p_2 = \frac{2W}{b} - \gamma H(2)$$

Where: γ is unit weight of collapsebody; H is height of collapsebody; W is gross weight of rockfall body; b is length of the weak interlayers in the lower collapse body (depth of rock cavity exclusive)**.**

There isn’tdeformation in the inside boundarydue to the unchangedstress state. According to the stress-strain relation of rocks, deformation linearly increases outwardto the maximum in the outer boundary, when load linearly increases from the inner boundaryto the outer boundary.

External boundary deformation in the lower soft rock:

$$\Delta s = \frac{2(W-\gamma Hb)}{bE} \ (3)$$

E indicates elasticity modulus of weak interlayers.B in (3) can be converted to variable value of rock cavity depth. There is a negative correlation of variable value withrock cavity depth in the formula, which is consistent with the conclusions of Chen et al’ study. (2009).

2.3 Deformation compatibility

Collapse body can be approximately assumedas a rigid body due to its generally large stiffness. Then, deformation of toppling type collapses can be considered asrotation of a rigid body. Therefore, deformation of lower rock cavities is in accordance with that of upper rock cavities, i.e. the rotation angles are the same.

$$\alpha = \mathrm{acrtan}\left(\frac{\Delta s}{b}\right) = \arctan\left(\frac{2(W-\gamma Hb)}{b^2E}\right)(4)$$

Upper rock body is seen as a rigid body, then fracture is considered to exist throughout the lower weak layer, and the width of tensional fracture must be related to the rotational angle.

$$\beta = \arctan\left(\frac{S}{H}\right)(5)$$

S is width of fracture and H is height of collapsebody. Then (4) is equal to (5), i.e.rotational angles are equal.

3 Warning model

The establishment of warning models corresponds to monitoring means. At present, the mainly monitoring means ofdeformation of collapse bodiesare displacement monitoring and monitoring of trailing edge fracture width variation, and so on. As a common monitoring means, fracture width variation can be safely used to estimate prewarningvalues.

The upper rock body has high strength and stiffness. As discussed above, the upper rock body was assumed to bea rigid body, and thefracture could extend to the weak layer when thedeformation of the rock mass is small. In this case, toppling-fracturing damagecan be converted to a sliding body.

According to limit equilibrium methods, width of fracture is up to maximum when rock body is in the limit equilibrium. The maximum of fracture width is achieved by the limit equilibrium equation of rock body as below:

$$f = \frac{W cosa \cdot tan\varphi + cL}{W sina} = 1 \ (6)$$

αis the sum of lamination orientation (θ) and rotation angle of rigid body (β), i.e., α =θ+β;L is the length of sliding surface, which is the width of body without the depth of rock cavity.

Equation (6) can be converted in the form of α equation:

$$\alpha = \varphi + \arcsin\left(\frac{cL}{W cos\varphi}\right)(7)$$

Equation (7) may then be combined with α=θ+β:

$$\beta = \varphi - \theta + \arcsin\left(\frac{cL}{W cos\varphi}\right)(8)$$

Combining (5) and (8) gives critical width of fracture:

$$s_{cr} = \mathrm{H} \cdot \tan\left[\varphi - \theta + \arcsin\left(\frac{cL}{W cos\varphi}\right)\right] (9)$$

Parameters in the formula can be obtained through field measurements.

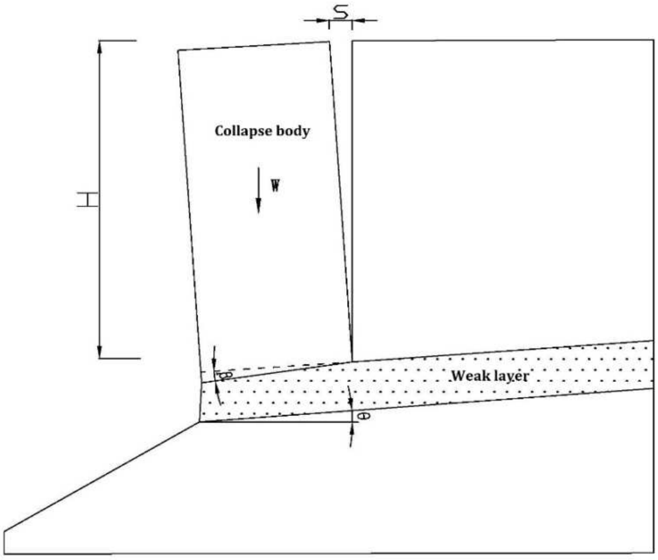

Fig.3: Sketch of slide block

4 Numerical analysis

In the model made by discrete element software, digging frontier is set to be rock cavity,slope rock is set to be sandstone and lower weak layer as mudstone. Rock cavities usually occur in mudstone environmentbecause mudstone is easily weathered.After weathering, mudstone shows a big variation in strength.Parametersof rock are selected with reference to thoseof the perilous rock belt inXujiaba, Wanzhou.

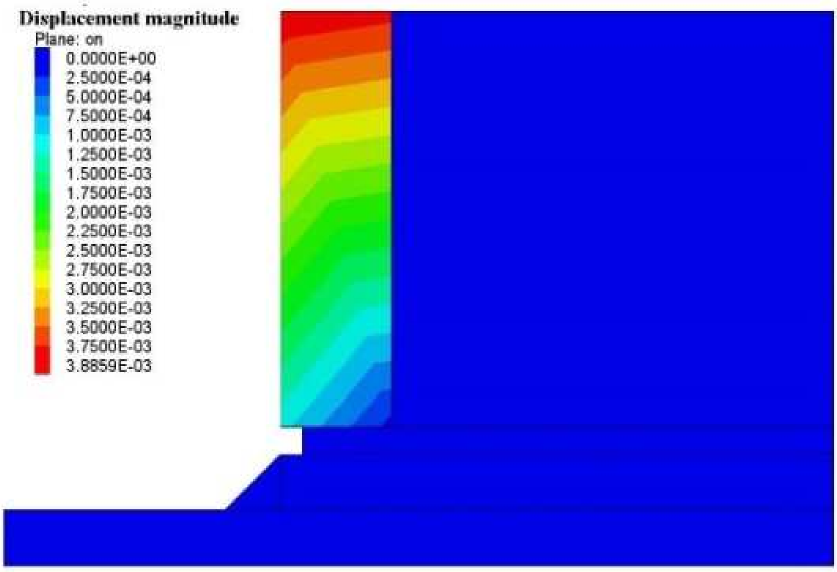

Fig. 4Three-dimensional model of the displacement diagram

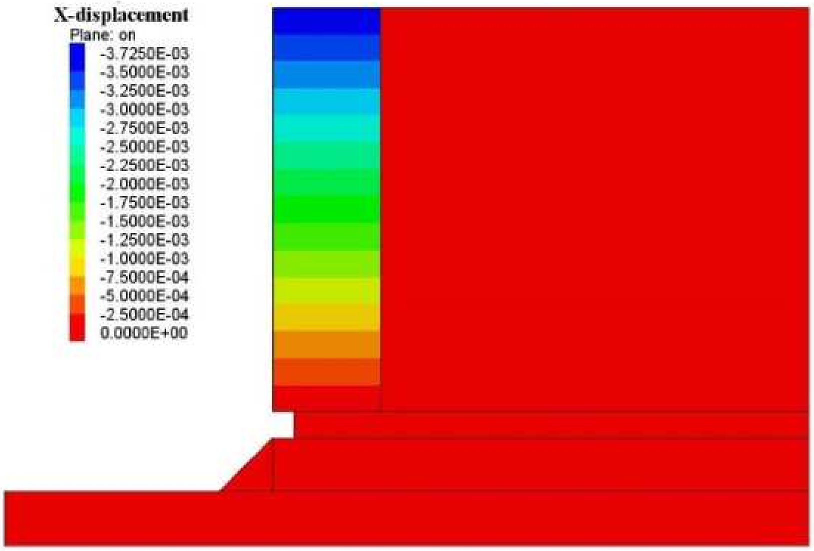

Fig. 5 Three-dimensional model of horizontal displacement diagram

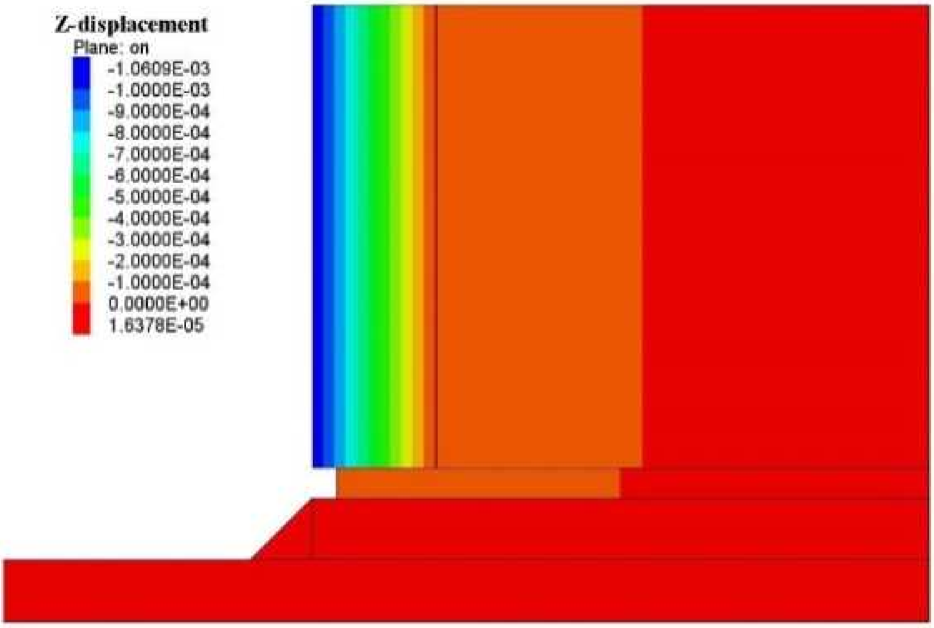

Fig. 6Three-dimensional model of the vertical displacement of the diagram

Three-dimensional model of horizontal and vertical displacement diagrams indicatesthat the horizontal displacement is principally linearly distributed (Fig. 5) and gradually decreases from top down, whereas the vertical displacement gradually decreases from outside to inside (Fig. 6). Three-dimensional model of the displacement diagram suggests that displacement is a linearly distributed from outside to inside (Fig. 4), and there isn't displacement change in the lower part of the fracture, which is consistent withthe previous assumption of the lower fracture seen as the end of stress influence. Dimensional model of the displacement vector diagram further verifies that the influence of the rock cavity on the lower part of the collapse body terminates at the lower part of the fracture (Fig. 7).

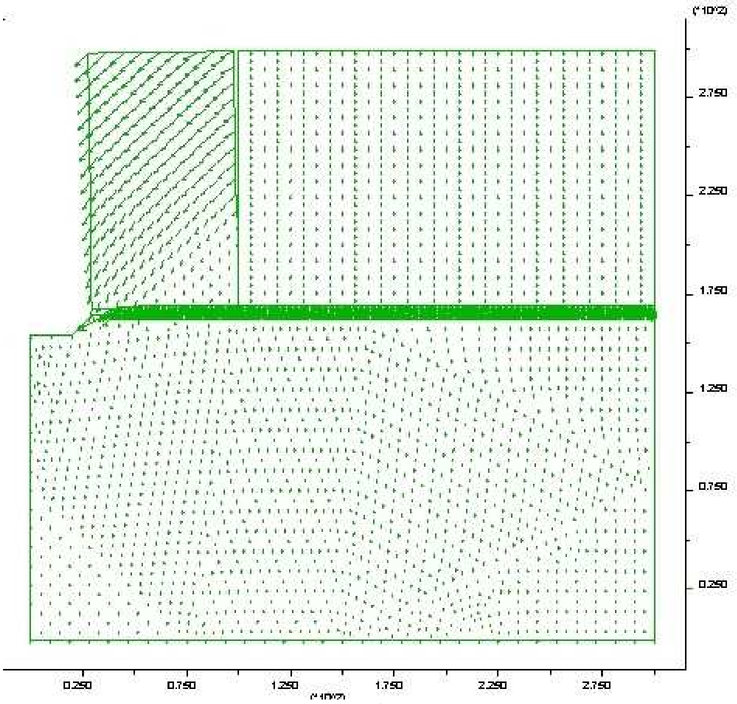

Fig7. Dimensional model of the displacement vector

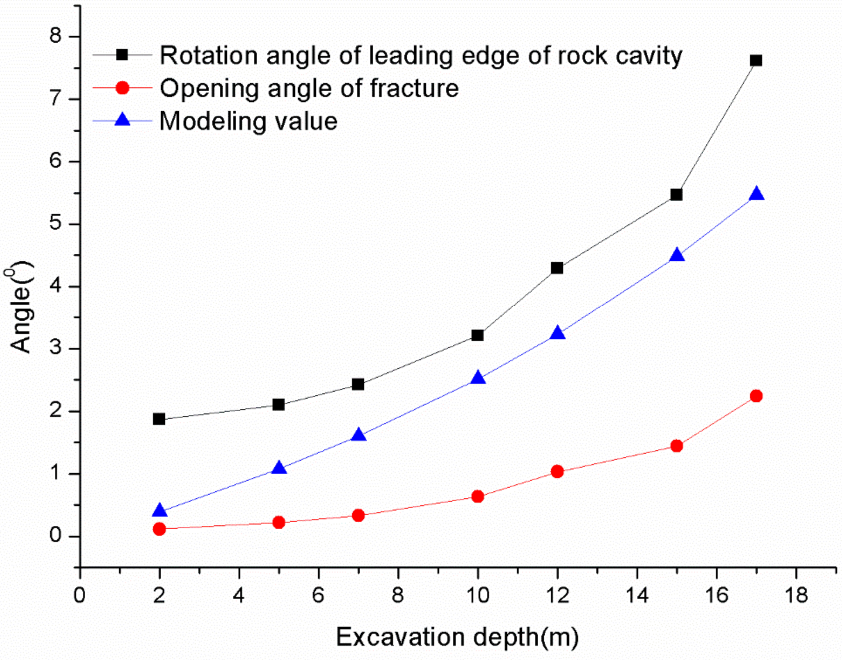

Fig. 8: Monitoring point angle and calculated values

The displacement monitoring was carried out in the upper part of the collapse body fractures and the outer edge of the rock cavity respectively.The results were converted into rotation angles andcompared with calculated values of the warning model’s rotation angles.

Table.1 Collapse body rotation angles

Excavation depth(m)	Rotation angle of rock cavity;(°)	Rotation angle of fracture(°)	Rotation angle of model(°)
2	1.865273	0.111506	0.391893
5	2.099905	0.219927	1.072149
7	2.424074	0.326582	1.597596
10	3.205216	0.630228	2.515248
12	4.289153	1.031213	3.2287
15	5.464666	1.440905	4.483741
17	7.613408	2.237804	5.466872

Table 1 and Figure 8 display that the calculated values of the model arelarger than the rotation angular values of the leading edge of rock cavity, and larger than the opening angular value of the upper fracture. The curves of model calculated value and the rotation angle of the leading edge of rock cavity show that the shapes and values are closeand the warning model is more similar to the deformation of the leading edge of the lower rock cavity. But, the shapes of thecurves are approximately identical.

CONCLUSION

Presumably, collapse body can be seen as a rigid body. Based on the stress-strain relation of rocks, this paper suggested that formation of collapse bodies must be consistent with changes of stress. Shapes of collapse bodies are unchangedbecause collapse body is rigid, thus the warning model can be presented with respect to the consistence of the upper and lower rotation angles of collapse bodies. Making a comparison among the results oftwo-dimensional and three-dimensional numerical models, as well as the computing result of warning model, we can conclude that the calculated values of warning model is larger than those of the rotation angles of the upper fracture and less than those of the rotation angle of the leading edge of rock cavity. Meanwhile, the model calculated curve is closer to the deformation curve of the lower rock cavity, while the three curves are basically similar, all being concave type.

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