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THE ROLE OF BLOCK RATIO AND LAYER THICKNESS ON ROCK SLOPES MOVEMENT STYLE

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ABSTARCT: In rock slopes, toppling movements are very common. The layers thicknesses and block ratio relative to slopes height might determine the type of slope movements and the style of toppling. In this paper, a numerical parametric study was conducted to evaluate the effect of block ratio and block thickness, in both crystalline and sedimentary rock formations, on the style of rock slopes movement in slopes prone to toppling. The mechanical defects or joints of rocks can be either random or well defined sets depends on the rock mass origin, metamorphic, igneous, or sedimentary. Different styles of movements were observed numerically in this study ranging from block toppling to rock falls. The styles of movement were also compared to the ones observed in the field. The results showed that the style movement is time dependent and three types of movement can be observed in one slope.

Keywords: Slopes, Sedimentary, Toppling, Bed-Height ratio

1. INTRODUCTION

Rock slopes can be divided into two main categories: structurally controlled slopes, such as the planer and wedge failures, and the non-structurally controlled slopes in which rupture surface penetrate the intact rock to form circular or spiral failure surface. The structurally controlled slopes normally fail by shear, sliding along one or more continuous discontinuities, whereas, in the non-structurally controlled slopes, failure is a complicated process and involves failure in both the discontinuity and the intact material [1]. The assumption that single discontinuity controls the slope failure is a simplified approach for analyzing rock slopes and is applicable only for small scale slopes, while for large slopes, the continuity has limited validity unless a fault or any continuous large rock structure existed prior to failure.

Different modes of toppling movements have been observed in the field on both anaclinal and cataclinal slopes. De Freitas and Watters [4] introduced the term "toppling" to describe the movements of rock slopes in rotation with steeply dipping beds. Goodman and Bray [7] extended the discussion of toppling mechanisms and showed that toppling in anaclinal slopes is possible. Goodman and Bray [7] identified three modes of toppling: flexural toppling, block-flexural toppling, and block toppling. Later, [6] explored toppling in cataclinal slopes and extended Goodman and Bray criteria for toppling to accommodate the underdip toppling. Figure 1 shows an example of a toppling movement.

Cruden and Hu [2] described 16 topples in the Highwood Pass in Alberta. These researchers identified three modes of toppling based on the field observation: block flexural toppling, which is characterized by gradual changes in the bedding orientation within the rock mass; multiple block toppling, which is characterized by more than one distinct zone of abrupt change; and block toppling, which is characterized by abrupt changes in the orientation between blocks between the toppling rock mass (the Chevron topple, [3]).

Fig.1 Rock falls/toppling in Hafeet Mountain, UAE.

Cruden and Hu [2] concluded that the different styles of toppling were associated with the joint spacing, bed thickness and slope angle, and used the block ratio to distinguish between different styles of toppling. Later, [5] further the investigation of the effect of the block ratio and concluded that using the block ratio to identify the toppling style is not the best way due to the overlap between the different modes of toppling. The following parametric study will investigate the effect of the joint spacing, the bed thicknesses, the slope angle, and joint-distribution on the style of toppling rock slopes by using the geological model proposed by [1].

2. GEOLOGICAL MODEL

Terzaghi [1] proposed a geological model for rock slopes in hard-unweathered rock masses. The mechanical defects of rocks can be either random or well-defined sets. He described the mechanical model of stratified sedimentary rocks:

"Stratified sedimentary rocks consist of layers with a thickness averaging between a few inches and many feet. These are commonly separated from each other by thin films of material with a composition different from that of the rest of the rock. The bedding planes are almost invariably surfaces of minimum shearing resistance. They are likely to be continuous over large areas. The cross-joints, generally nearly perpendicular to the bedding joints, are commonly staggered at these joints. The cohesive bond along the walls of the cross-joints is equal to zero.

The intersections between the cross-joints and the bedding planes may be more or less parallel to one of two or more directions, or less parallel to one of two or more directions, or less commonly, the intersection may have a nearly random orientation. Because of the almost universal presence of bedding or cross-joints, stratified sedimentary rock with no effective cohesion (Ci=0.0) has the mechanical properties of a body of dry masonry composed of layers of more or less prismatic blocks which fit each other. The boundaries between the individual layers of blocks constituting the masonry correspond to the bedding planes of the rock. The cohesion across the joints between all the blocks of each layer is zero, and most of the joints between the blocks of two adjacent layers are staggered at the boundaries between layers. The stability of a slope on a rock with the mechanical properties of such a body of masonry depends primarily on the orientation of the bedding planes with reference to the slope". Cruden [8] also observed the same geological model. Terzaghi [1] also described a geological model for the crystalline rocks such as marble or granite as irregular-shaped crystalline particles, which fit each other like blocks between joints in a rock with a random joint pattern. The above-mentioned geological models are adapted in the present study.

3. THE NUMERICAL MODEL

Terzaghi [1] and Cruden [8] described conceptual geological formations for rock masses in both sedimentary and crystalline rocks. Four numerical models, A, B, C, and D, were built based on the description of the geological model of rock masses, proposed by [1] and [8], to examine the effect of the block geometry and the slope face angle on the movement modes of rock slopes. The basic Numerical model used in this analysis is presented in Figure 2. It shows the details of the jointing and the slope face angle variation between 45°-60°. The bedding was kept at a constant dip of 80°, while the bed's thicknesses were varied from 1.5 m to 3 m to 6 m for each slope.

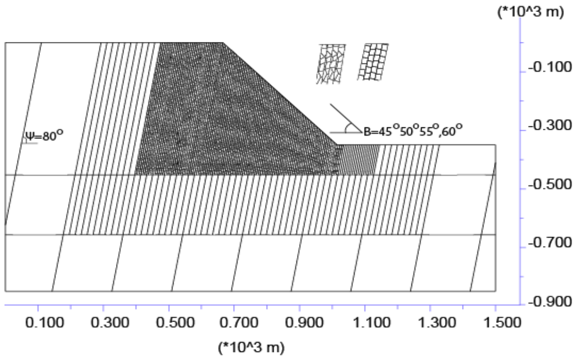


Fig. 2 Illustration of the numerical model geometry and joints details inside the beds

The effect of the bed's thickness and the slope face angle were tested by using two patterns of joints distributions. The first joint pattern was uniformly distributed and perpendicular to the bedding to simulate stratified sedimentary rock. The second pattern was irregular joint pattern intersecting the beds at different angles wad used to simulate crystalline rocks. The insert in Figure 2 shows the joints patterns used in the numerical model. For the 45° models, the cross-joints were also changed from 8 m to 4 m to 2 m, to investigate the cross-joints spacing effect on the slope deformation style, producing block ratios between 5 and 0.1. A total of 30 models with different geometries were modeled and monitored to determine the toppling modes and behavior with numerical time. Table (1) shows the geometrical setup of the slopes used in this parametric study.

Table 1 Geometries of the toppling slopes used in this study

Slope	Face Angle (°)	Bed thickness (m)	Cross-joints spacing (m)
A	45	6, 3, 1.5	8, 4, 2
B	50	6, 3, 1.5	8
C	55	6, 3, 1.5	8
D	60	6, 3, 1.5	8

4. STRENGTH PROPERTIES

According to [1] and [8], the cross-joints and the beds have no cohesion, and the friction angle of the rock mass is the only strength parameter involved in stability analysis of the slopes. In this analysis, the cohesion and the tensile strength were assumed to be equal to zero, and a friction angle of 30° was used for both the cross-joints and the steeply dipping joints. The cohesion along the beds can be easily destroyed and becomes equal to zero [1].

Although Patton [9] showed that the friction angle of rocks was composed of two components, the basic friction angle and the asperities, Cruden [10] showed that the friction angle in the Canadian Rockies could be reasonably estimated as the basic friction angle and zero angles of the asperities. Based on an experimental study using a tilt table, Hu and Cruden [11] concluded that the friction angle could have a range from 21.5° to 41.4°. Cruden [8] used a friction angle of 30° to build a process diagram to describe the type of slope movement based on the slope face and the beds' orientation. Table 2 shows the properties used in this parametric study for both the beds and the cross-joints.

Table 2 Elastic blocks and joints properties

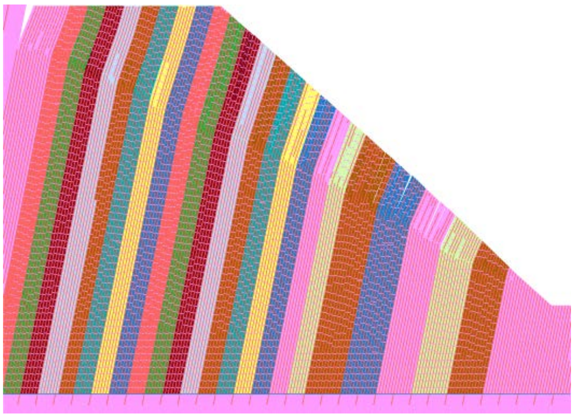
Property	Elastic blocks	Joints
E (MPa)	20000	
Poison's ratio	0.25	
ϕ (°)		30
C (MPa)		0
σ_t (MPa)		0
Kn (GPa)		20
Ks (GPa)		5

5. MODES OF TOPPLING

Three modes of toppling were observed numerically: block-flexural toppling, multiple block-toppling, and block toppling (Chevron). Table 1 shows the different slopes' configurations used in this paper. All of these slopes are prone to toppling according to the Goodman and Bray's criteria. The effect of the block geometries and the slope face angle on development of the toppling mode investigated. The slopes were monitored with cycling to observe the mode of toppling formed. As topples deformed with cycling the style of toppling changed from flexural toppling to multiple toppling and eventually block toppling, the toppling style kept changing as cycling continued.

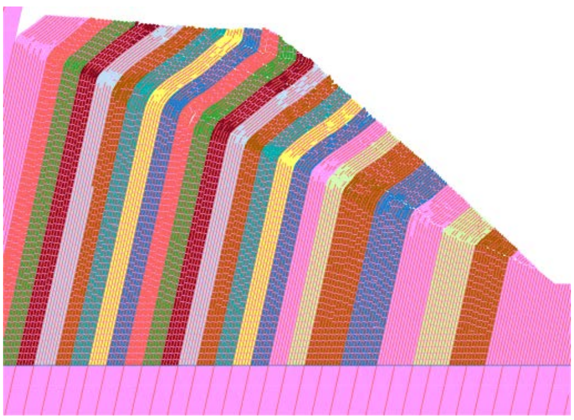
Figure 3(a) shows slope A (45°) with 3 m bed thickness and 8m cross-joints. This slope shows a gradual rotation of the rock columns with no rupture surface formation and experienced block flexural toppling mode. Cruden and Hu [2] and McAffee and Cruden [5] found block flexural toppling with no rupture surface formation in Highwood Pass topples.

The model in the figure is shown at 40,000 cycles. By allowing the model to cycle, two or more rupture surfaces were formed inside the slope: a pivot lower rupture surface and upper rupture surfaces, which formed a multiple block toppling that is characterized by more than one rupture surface, Figure 3 shows the model at 120000 cycles. As the model allowed deforming with cycling, the toppling continued around the lower pivot rupture surface and the blocks above the upper rupture surface continued to topple. Eventually, the slope moved gradually from the multiple block-toppling to block-toppling mode which was described by [3] as Chevron, Figure 3 shows the model at 320000 cycles.



a) Block-flexural toppling, 40,000 cycles

b) Multiple block toppling, 120,000 cycles



c) Block toppling, 320,000 cycles

Fig. 3 Development of toppling style with time, (a) block-flexural toppling, (b) multiple block toppling, and (c) block toppling.

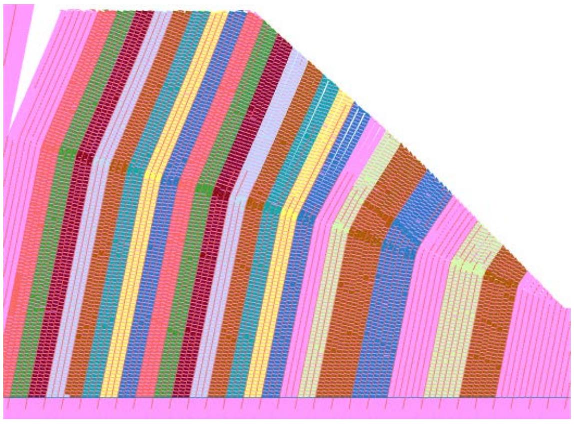
This deformation process and moving from stage to stage was observed in all the toppling models used in this study, for both regular and irregular cross-joints patterns, i.e. time is important factor in determining the toppling styles observed in the numerical simulation, the style is controlled by the time allowed for the slope to deform and move from stage to stage. McAffee and Cruden [5] concluded that weathering, which is time dependent process, caused the toppling to occur at the Highwood Pass. The next section will discuss the effect of the bed thickness normalized to the slope height as opposed to the block ratio on the toppling style.

6. BED THICKNESS VERSUS BLOCK RATIO EFFECT

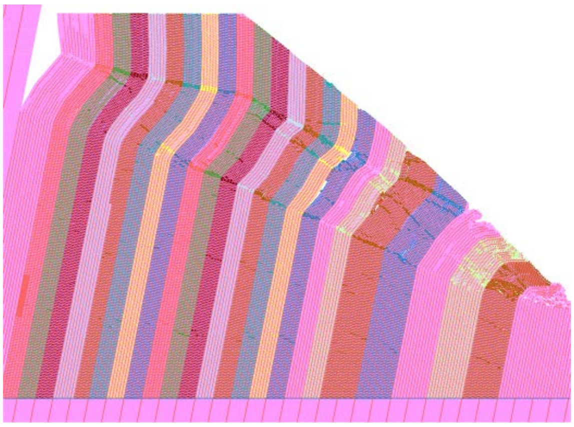
To normalize the bed thickness, the bed-height ratio is defined as the bed thickness to total slope height. Cruden and Hu [2] studied the effect of the block ratio on the toppling mode and suggested that the block ratio can determine the style of toppling. Two models with the same block ratio but different bed-height ratios were set up and tested numerically to determine if the toppling mode controlled by the block ratio or the bed-height ratio (1.5 block ratio and bed-height ratios of 0.017 and 0.0085 corresponds to 6 m and 3 m bed thicknesses, respectively). The two models had a 45° slope face. The slopes were monitored with time and compared at the same number of cycles (120000) and at the same numerical time (25 seconds).

Figure 4 shows the two models at 25 seconds. The slopes experienced two different modes of toppling despite that the same block ratio was used. The 0.017 bed-height ratio slope shows a block-flexural toppling while the 0.0085 bed-height slope shows a multiple block toppling at the same number of cycles. These results suggest that bed-height ratio, rather than the block ratios, plays an important role in determining the toppling style.

Martin and Kaiser [12] discussed the effect of the internal shears on rock slopes and showed the importance of these internal shears to accommodate failure along the basal shear plane. As mentioned earlier, the bed-height ratios were varied from 0.0043 to 0.017 to investigate their effect on the toppling mode as opposed to the effect of the block ratio in order to explain the mode of toppling. The smaller bed-height ratios introduced more shear planes in the rock mass than the high bed-height ratio, along which more sliding and shearing occurred at the instance at which the rock slope started moving. As the bed-height ratio became smaller the numerical simulations showed smoother rotational movements for the thin beds than for the thick beds. The comparisons between the different models were always made at the same number of cycles or the same numerical time.



a) Block-flexural toppling, 0.017 bed height (25 seconds)



b) Multiple block toppling, 0.0085 bed-height (25 seconds)

Fig. 4 Comparison of toppling style for two slopes at the same block ratio and different bed-height ratios, a) 0.017 bed-height ratio, b) 0.0085 bed-height ratio.

According to this numerical model parametric study, the rupture surface or pivot line also affected by the bed-height ratio, the thinner the beds, the steeper the rupture surface for the same slope face angle. Figure 5 shows the 55°slopes at three bed-height ratios, 0.017, 0.0085 and 0.00425, as shown in Figure 5, the rupture surface or the pivot line is shallower for the small bed-height ratio than the large bed-height ratio. In all the models, an uphill back scarp formed (see Figure 5), notice depth of the uphill back scarp in the models, it increased as the bed-height ratio increased.

This behavior occurred because the thin beds will introduce more shear planes, which allow more sliding and shearing between the rock columns than the thick beds (6 m) allowed. These shear planes between the beds accommodated more internal shearing and displacement and resulted in a smoother toppling movement than the toppling of the thick beds and shallower pivot or rupture surface.

Due to the increased amount of shear planes in the low bed-height ratio's slopes, the deformation due to the toppling movement was accommodated by shorter columns, and the pivot line or the rupture surface was formed closer to the surface and was steeper for the low bed-height ratio's slope than the high bed-height ratio's slopes, the rupture surface angle from the horizontal was measured and found to be as following: 28° for the 0.017 bed-height ratio, 31° for the 0.0085 bed-height ratio and 33° for the 0.0043 bed-height ratio.

7. EFFECT OF THE SLOPE FACE ANGLE

At this parametric study, four slope face angles were modeled 45°, 50°, 55° and 60°. The results show that the mode or style of toppling was not affected by the slope face angle. By comparing the slopes at different face angles and the same bed thickness, the slopes were found to behave in the same pattern with the three modes of toppling: block-flexural, multiple blocks toppling and block toppling.

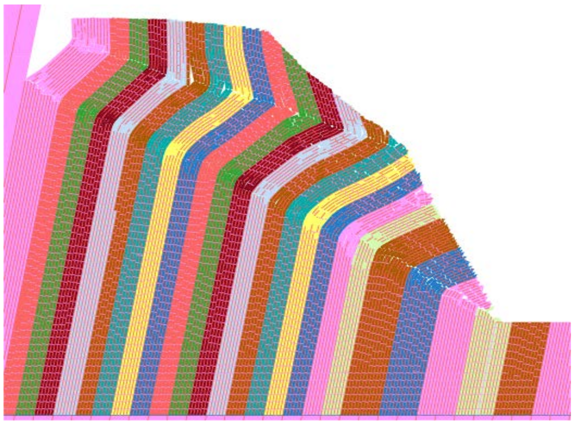
The low bed-height ratio slopes required more time to pass through this process of toppling, and in some cases it might need fracturing or removal of the failed material at the toe of the slope. The monitoring of the models showed that, the uphill scarp depth increased as the slope face increased, the uphill scarp for the 60° slope (0.017 bed-height ratio) was 123 m while the uphill scarp depth for the 45° was 83.4 m. This result was due to that, at steeper slopes the stresses was greater which resulted in higher stress-induced deformation. The high stress-induced deformations were accommodated by shearing along longer and deeper portions of the columns along the interface between the beds, and this resulted in deeper uphill scarp.

8. ROCK SLIDES AND ROCK FALLS

Toppling movement is characterized by shearing along the beds and rotation around the pivot line. This rotational movement may result in the formation of a rupture surface if enough rotational movement allowed.

This rupture surface evolves from the toe of the slopes, and propagates up the slope. Depending on the amount of rotation of the rock columns, the rupture surface may form partially or completely through the rock mass, i.e. through progressive development. Cruden and Hu [2] found topples that had been displaced by sliding along the rupture surface. The simulation revealed that the rupture surface was always initiated at the foot of the slope and propagated as the columns rotated and extended into the slope. In all models, the higher bed-height ratio slopes developed a rupture surface faster than the low bed-height ratio because the thin beds allowed more gradual rotation and smoother curvature through the rock columns than the thick beds. Slopes with a 45° and 55° slope face angle tended to develop slopes susceptible to slide.

a) Block toppling, uphill scarp depth = 106.3 m, rupture surface at 28°



b) Multiple block toppling, uphill scarp depth = 83.8 m, rupture surface at 31°

c) Bed-height ratio = 0.00425

Fig. 5 55° slopes with three bed-height ratios and same number of cycles 320,000.

If further fracturing occurred and/or the cross-joints were more closely spaced, the rock will slide and the debris will move down the slope. A slope with a 45° slope, 0.0085 bed-height ratio, and 2 m cross-joints were used to examine if sliding will occur at closer spaced cross-joints than 8 m.

Figure 6 shows the slope at failure and the sliding mass down the toe of the slope. In natural slopes, if natural damping did not stop the sliding mass, the material may travel away from the slope, as these failures may fail catastrophically at a high speed. McAffee and Cruden [5] noticed that five of the slopes at the Highway Pass developed a sliding mass away from the slope area. Note that rock falls were developed in the slopes with 55° and 60° degrees slope face angles especially at the 0.017 bed-height ratio. As the columns bent, the rock up the slope moved from flexural toppling, to multiple blocks toppling, to block toppling. At the stage of block toppling, the rocks at the top of the slope tended to detach from slope and fell catastrophically at very high speed, Figure 7 shows rock falls.

This behavior was observed more in the high bed-height ratio than the 0.085 and 0.0425 ratios because the slopes with high bed-height ratio moved easier and faster to block toppling stage, and left the upper part of the slope unsupported. The 0.0085 and 0.00425 bed-height ratio slopes tended to develop rock falls at the toe of the slopes. If erosion or any natural process removed the displaced material from the toe of the slope, or if the natural damping did not stop the rock falls at the toe the slope, the slopes would continue to move toward the block toppling stage and develop rock falls.

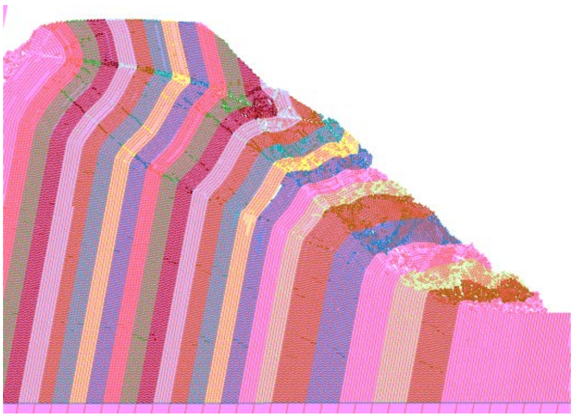


Fig. 6 Sliding proceeded by toppling

9. TOPPLING IN CRYSTALLINE ROCKS

Unlike the sedimentary rock slopes discussed above, the foliated crystalline rocks may contain cross-joints with an irregular joints pattern. These joints can form at any angle with the steeply dipping joints. Nichol et al. [13] reported toppling in metamorphic and igneous rocks in natural rock slopes. This geological model is susceptible to toppling due to the presence of the steeply dipping joints. As the cross-joints intersected the beds in different angles, the cross-joints were required to rotate and move more than the sedimentary rocks perpendicular cross-joints to form rupture surface. UDEC-DM [14] was used to create an irregular joints pattern at a random orientation inside the rock mass that contained steeply dipping joints (see the insert in Figure 2).

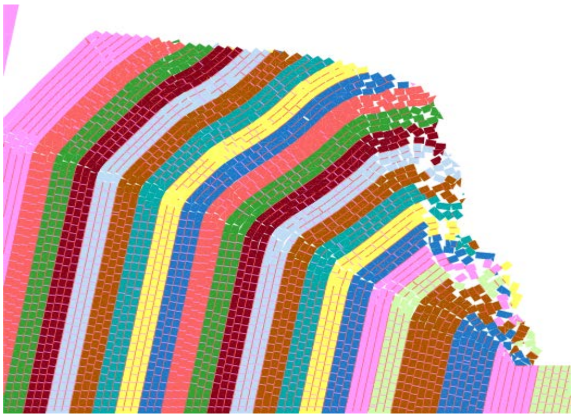


Fig. 7 Rock falls at 60° slope face angle and 0.017 bed-height ratio

The toppling mode, displacement, and formation of rupture surface were monitored and showed a similarity with the behavior of the sedimentary rocks. By comparing the two joints' patterns, the regular and irregular one, the later pattern was found to provides more planes that could accommodate sliding and shearing in the direction of the steeply dipping joints than the first pattern as the irregular joints' pattern contained joints in variable directions and some cross-joints might also have had the same orientation as that of the main joint set, which resulted in a steeper rupture or rotation surface than that of the sedimentary rocks. The three stages of toppling; flexural-block toppling, multiple blocks toppling, and block toppling occurred in these slopes, however, this behavior was more obvious in the sedimentary rocks.

Figure 8 shows the 60° foliated crystalline slope with a 0.017 bed-height ratio and irregular joints' pattern. By comparing Figure 8 and Figure 7, the two slopes at the same number of cycles, two different modes of toppling can be identified as the different joints orientations allowed shearing to be accommodated near the surface and delayed the transition from multiple block to block toppling. Further cycling permitted more deformation, which resulted in block toppling, Figure 9 shows the model at 720,000 cycles, this stage can be characterized as block toppling, notice the block falls, due to high slope face angle. Figure 10 shows an example of rock falls of steep slope. The slope shown in Figure is an example of a slope prone to topple; the rock falls are shown at the heel of the slope.

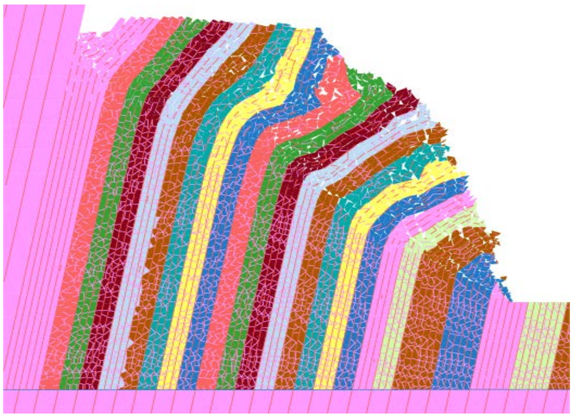


Fig. 8 Toppling at 60° slope face, and irregular joints pattern at 320,000 cycles

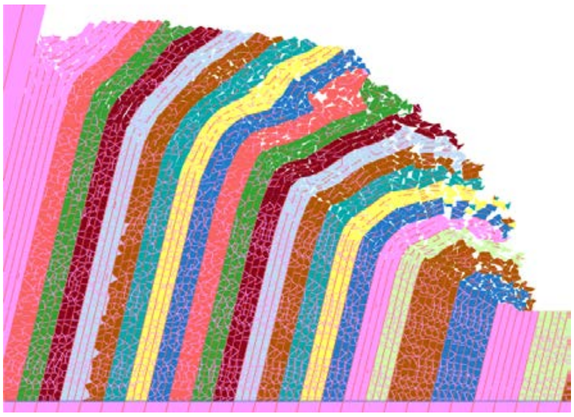


Fig. 9: Block toppling and rock falls, 60°slope, and 0.017 bed-height ratio at 720,000 cycles

10. CONCLUSION

According to the numerical results presented in this study, the toppling style is more likely to be controlled by the time allowed for the slope to deform and move from stage to stage, the slope prone to topple moves with time from block-flexural toppling stage to block-toppling stage. The numerical modeling results suggest that bed-height ratio, rather than the block ratios, plays an important role in determining the toppling movement style. The smaller bed-height ratios introduced more shear planes in the rock mass than the high bed-height ratio, along which more sliding and shearing occurred at the instance of rock slope movement.

According to this parametric study, the rupture surface or pivot line also affected by the bed-height ratio, the thinner the beds, the steeper the rupture surface for the same slope face angle. In the field weathering with time, since the onset of toppling, might play an important role in controlling the movement style or stage. The steeper the slope the higher possibility of developing rock falls. The rupture surface was initiated at the foot of the slope, as the columns down the slope were susceptible to more rotation than the columns up the slope.

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