Observations and evaluation of floor benching effects on pillar stability in U.S. limestone mines

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ABSTRACT: A survey of roof and pillar conditions in underground limestone mines in the United States has revealed that bench mining of the floor between pillars can cause instability in the pillars at the perimeter of the benched area. Increased loading of these pillars was observed at several mines. Large inclined geological structures that are exposed in pillar ribs were observed to contribute to pillar instability. The paper describes a study that was carried out using numerical models to assess the effects of bench mining on pillar load and stability. It was found that the benched pillars shed load onto the surrounding pillars owing to their reduced stiffness. The pillars at the perimeter of the benching area will start shedding load as soon as benching increases the height of one side of the pillar. A case study is described which shows the effects of bench mining on limestone mine pillars.

1 INTRODUCTION

Underground limestone mines in the U.S. make use of the room and pillar method of mining. Bench mining of the floor between the pillars is sometimes carried out to improve utilization of the reserves. Figure 1 shows an area where bench mining of the floor is underway. The benched pillars are in the foreground and the original development pillars are seen in the background. The National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory is investigating pillar and roof stability in U.S. limestone mines. Observations of pillar conditions carried out as part of this study revealed that the condition of pillars around the perimeter of bench mining operations can be worse than elsewhere in the mine. Unstable pillar ribs represent a rock fall hazard to mine personnel. Over the decade from 1996 through 2005, ground falls were the cause of 36% of fatalities and 12% of all injury related lost workdays in underground limestone mines (Mine Safety and Health Administration, 2006). In addition, failure of a single pillar can result in overloading of the adjacent pillars, possibly resulting in the collapse of multiple pillars.

A total of 31 different mine sites were visited by NIOSH researchers. Bench mining of the floor had been carried out at 18 of the 31 mine sites visited. Evidence of increased instability of the pillars at or near the perimeter of the benched areas was observed at six of these mines. The observed instability was in the form of failure along pre-existing geological structures and stress related spalling and fracturing of the pillar ribs.

Figure 1. Example of bench mining of the floor between pillars in a limestone mine.

This paper presents a summary of the observations made and the results of numerical analyses that were carried out to evaluate the changes in loading and pillar strength that occur during bench mining. A case study of pillar instability associated with bench mining is presented. The paper concludes with suggestions for identifying situations that are likely to result in instability during bench mining and strategies to limit the potential for instability.

2 FIELD OBSERVATIONS OF BENCH MINING IN LIMESTONE MINES

Field data on roof and pillar conditions were collected at 86 different locations in 31 limestone mines in Pennsylvania, Virginia, West Virginia, Illinois, Kentucky, Tennessee, Missouri and Indiana. The data collected at each location included rock mass properties, pillar and room dimensions, information on roof and pillar stability and rock strength properties, (Esterhuizen et al. 2006). The rock mass in these limestone mines can be classified as "Good" to "Very Good" with rock mass rating (RMR) values in the range of 70-85 units, using the Bieniawski (1989) method of classification. The intact rock strength is in the range of 100-200 MPa. Table 1 presents a summary of the dimensions of pillars and rooms showing both development and benching dimensions at the 31 mines. It can be seen that bench mining increases the average pillar height from 7.8 to 17.8 m and reduces the average the width-to-height (W:H) ratio of the pillars from 1.67 to 0.95.

Table 1. Dimensions of room-and-pillar mining layouts.

Parameter	Average	Minimum	Maximum
Pillar height: development (m)	7.8	4.8	10.7
Pillar height: benched pillar (m)	17.8	9.9	38.0
Pillar width (m)	13.9	5.1	28.6
Pillar W:H: development	1.67	0.93	3.52
Pillar W:H: benched pillar	0.95	0.29	2.35
Room width (m)	13.5	9.1	16.8
Depth of cover (m)	121	23	533
Local percent extraction (%)	73	54	88

Observations of pillar conditions at the mines revealed several instances where the partially benched pillars at the edge of the benching operations had become unstable. Table 2 summarizes the cases in which pillar instability associated with bench mining was observed. Case 3 was evaluated in greater detail and is presented as a case study. Benching operations were halted in two of the observed cases owing to instability of the partially benched pillars. Several cases were observed in which the pillars at the perimeter of the benching area showed signs of increased loading. In addition, instability was observed when bench mining exposed large joint structures in the pillar ribs.

It was apparent from the field observations that benching not only reduces the pillar strength by increasing the pillar height, but also causes an increase in pillar load at the perimeter of the benched area. The increased pillar load can be ascribed to the fact that the benched pillars are taller and are consequently less stiff than the surrounding development pillars. Stresses are concentrated in the stiffer development pillars, which can result in instability in these pillars.

The average pillar stress shown in the table was calculated using the tributary area method, which does not account for increased loading owing to the variable stiffness of the benched and development pillars. Numerical model analyses were conducted to further quantify the load and strength changes caused by benching and evaluate their impact on pillar stability.

3 NUMERICAL ANALYSIS OF THE EFFECT OF BENCHING ON PILLAR STRENGTH AND LOADING

The summary of mining dimensions in Table 1 shows that the average width-to-height (W:H) ratio of pillars is reduced by 43% during benching operations. The effect of the increased height on pillar strength can be estimated using one of the published pillar strength equations for hard rock mines, such as the equation developed by Hedley

Table 2. Summary of observed pillar instability associated with bench mining.

Case	W:H Develop	W:H Benched	Average Pillar stress (MPa)	Instability Observed
1	1.3	0.59	13.1	Large discontinuities exposed by benching, evidence of high horizontal stress, diagonal shearing through pillar. Benching was halted.
2	1.5	0.73	14.1	Progressive spalling of pillar ribs, pillar width reduced significantly, weak bedding infill contributed to spalling.
3	1.5	0.44	15.0	Spalling of several pillars to hourglass shape. Sloughing from one of the pillars caused by a large steeply dipping discontinuity.
4	1.65	0.61	8.14	Sloughing from pillar ribs as a large discontinuity is exposed at the perimeter of benching.
5	2.0	0.99	19.8	Sloughing from pillar walls at location of a large discontinuity. Benching was halted and resumed beyond this area.
6	1.96	0.92	13.1	Spalling to hourglass shape. Benching halted owing to presence of large discontinuities in adjacent pillars.

and Grant (1972). However, during benching, the height of a pillar is progressively increased as each side is benched, until all four sides are fully benched. The strength of a pillar during these stages of bench mining cannot be determined using existing pillar strength equations since the equations are intended for prism shaped pillars that have equal height on all sides. Numerical models were therefore used to estimate the strength of the irregular shaped pillars formed during benching. Figure 2 shows conceptually the stages of benching around a limestone pillar that were considered in the models. During Stage 1 one side of the pillar has been bench mined. At Stage 2, two sides have been benched and so on, until the pillar is fully benched in Stage 4. Numerical models were also used to investigate the changes in average pillar stress at each stage of bench mining.

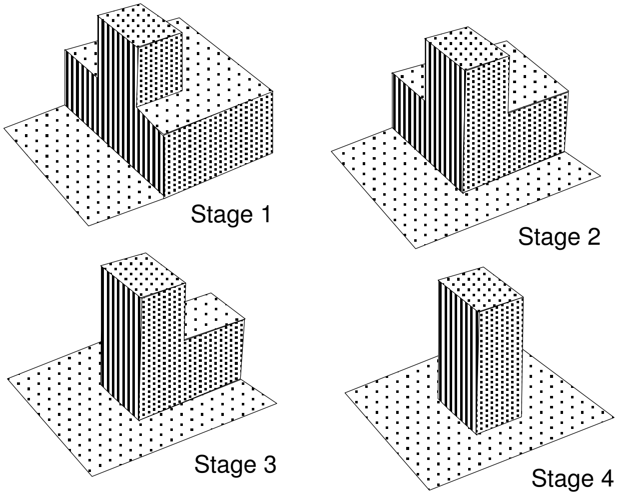

Figure 2. Stages of bench mining around a pillar considered in the numerical models.

3.1 *Analysis of the Strength of Partially Benched Pillars*

The progressive reduction in pillar strength during bench mining was assessed using the FLAC3D finite difference program (Anon, 2005). Models were set up to simulate square pillars with initial W:H ratios of 1.0 and 1.5. The benching stages shown in Figure 2 were modeled by progressively removing the floor rocks on each side of a pillar until it is fully benched on all sides. The benching depth was selected so that the pillar height was doubled during the benching procedure. The model geometry for the pillar with initial W:H = 1.0 is shown in Figure 3. Model element sizes were kept constant during all the runs to avoid element size effects on the results.

The mechanical properties that were used to simulate the limestone rock mass are summarized in Table 3. The properties were selected to model a rock mass with an RMR value of 70 and intact rock strength of 120 MPa. A bi-linear peak strength criterion with strain softening of the failed rock was used to capture both brittle spalling and shear failure of the limestone, as suggested by Kaiser et al. (2000), Martin & Maybee (2000) Diederichs (2002) and Diederichs et al. (2002). The brittle rock strength was set at 33% of the intact rock strength and the Coulomb strength properties of the rock mass were based on the Hoek-Brown (1997) criterion. Details of the modeling approach and selection of input parameters for this model are presented in Esterhuizen, (2006).

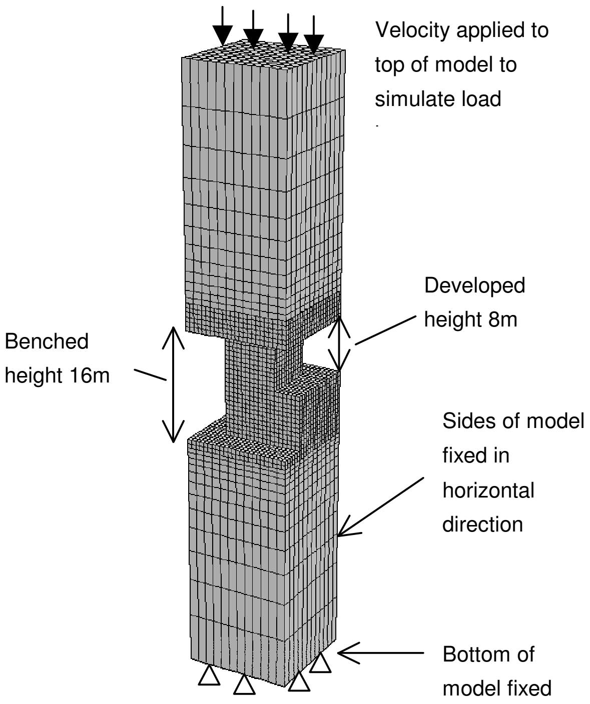

Figure 3. FLAC3D model of a partially benched pillar

Table 3. Input Parameters for the bilinear strength model.

Parameter	Value
Elastic modulus	70 GPa
Poisson ratio	0.2
Intact rock strength (UCS)	120 MPa
First stage (brittle) cohesion	20 MPa
First stage (brittle) friction angle	0º
Second stage cohesion	6.5 MPa
Second stage friction angle	42.7º
Tensile strength	7 MPa
Dilation angle	30º

The strength of the modeled pillars was determined by gradually increasing the vertical load in the models. Failure of the rock in the models was allowed to occur in response to the increased loading. The loading was increased until the pillar started to shed load. The pillar strength was defined as the peak vertical load, divided by the horizontal cross-sectional area of the pillar. The selected input parameters resulted in pillar strength of 48 MPa for a square pillar with W:H=1.0, which is 40% of the intact rock strength of 120 MPa used in the models. The model shows good agreement with the empirical equation of Hedley and Grant (1972) for square pillars with W:H of 0.75 to 2.0.

Model results for pillar strength at the various stages of bench mining are presented in Figure 4, which shows how the pillar strength is progressively reduced as bench mining is carried out around the pillar. The model results show that strength of the pillar with W:H=1.0 is reduced by about 16%, from its initial value of 48 MPa to a final value of 40 MPa. The pillar with W:H=1.5 experiences a reduction in strength of 37% from the development stage to the fully benched stage.

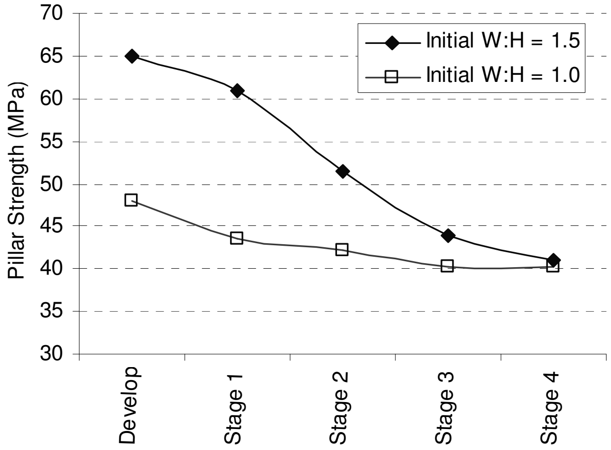

Figure 4. Results of FLAC3D modeling showing strength reduction of pillars with initial W:H=1.0 and 1.5 from initial development through various stages of bench mining. Final W:H ratios at Stage 4 are 0.5 and 0.75 respectively.

From a pillar design point of view, it is important to also know how bench mining affects the pillar loads while the strength reduction is occurring. This aspect was assessed using numerical models and is discussed below.

3.2 *Analysis of Changes in Pillar Loading During Benching*

The examine 3D (Anon, 1998) boundary element package was used to determine how the pillar load is likely to change in response to benching. The program allows an array of pillars to be modeled in three dimensions assuming elastic rock properties. Benching of the floor can be modeled realistically and deflection of the roof over the benched and development pillars is simulated.

The rock mass was modeled with a Young's modulus of 30 GPa, to account for rock mass discontinuities, and Poisson's ratio of 0.2. The field stresses were set up to simulate a horizontal to vertical stress ratio of 2.0 at a depth of 200 m. The models simulated an array of pillars each 12 m wide and having W:H ratios of 1.0. The floor of the model was removed in stages to simulate benching to W:H of 0.5. The rooms were equal in width to the pillars, resulting in 75% extraction of the modeled limestone. Figure 5 shows a cut-away view of the model in which the initial developed pillars, the perimeter pillars and the benched pillars can be seen.

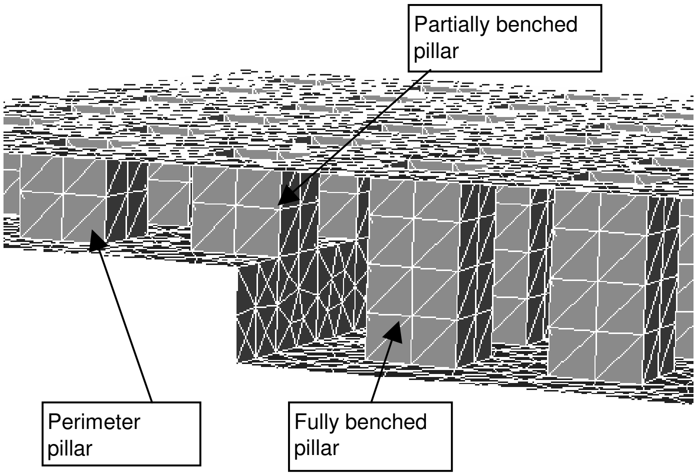

Figure 5. Cutaway view of Examine 3D model showing development and benched pillars.

Figure 6 shows the average stress in the pillars obtained from a model in which half of the pillars have been benched. The results show that the development pillars at the edge of the benched area are subjected an increase of about 12% in their average stress. The results further show that the stress in the partly benched pillar is lower than the stress in the adjacent pillar that has not been benched yet, indicated as "perimeter pillar" in Figures 5 and 6. The lower stress in the partly benched pillar can be explained by the fact that its stiffness is reduced by the increase in height of one of the sides of the pillar, causing the load to be transferred to the stiffer development pillars. It can clearly be seen that the fully benched pillars are at a reduced stress level, owing to their relatively low stiffness. As benching continues, the stress in the fully benched pillars is expected to gradually

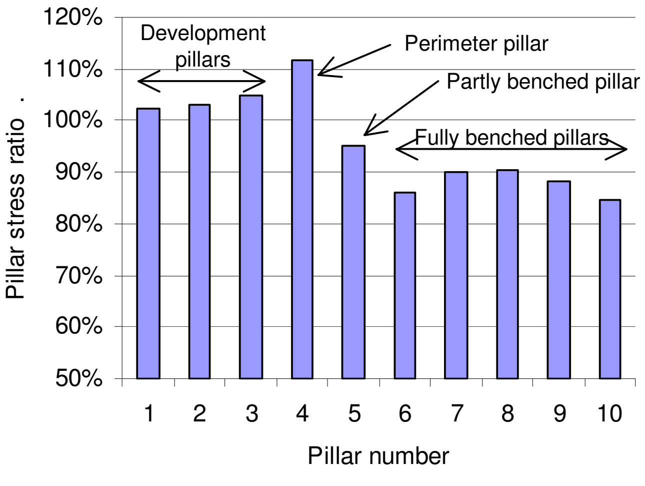

Figure 6. Results of Examine 3D model showing the average pillar stress during bench mining as a ratio of the average pillar stress prior to bench mining.

increase back to the tributary stress.

Further results, showing the changes in the average vertical stress in a pillar at the various stages of bench mining are presented in Figure 7. The figure also shows the associated changes in the pillar strength for a pillar with W:H=1.5, as previously presented in Figure 4. It can be seen that the pillar stress is a maximum just before benching starts around the pillar. As soon as one side of the pillar has been benched, the average pillar stress decreases, owing to the increased height and reduced stiffness. The average pillar stress continues to decrease as benching progresses, until the pillar is fully benched. The stress in the fully benched pillars will gradually rise as the benching face moves away. Full tributary loading can re-establish in the benched pillars if the mined area is sufficiently large.

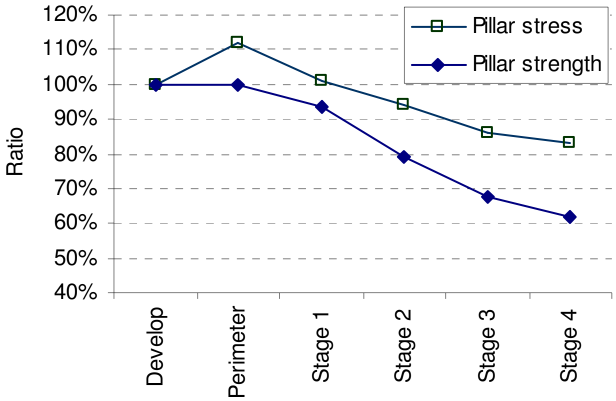

Figure 7. Change in the average vertical pillar stress and strength during various stages of bench mining, for a pillar with W:H=1.5 based on FLAC3D and Examine3D results.

These results indicate that bench mining activities will result in an increase in the pillar stress around the perimeter of the benched area. However, once the pillar is partially benched, the average pillar stress will decrease.

3.3 *Stress Concentration and Damage*

The numerical models confirm that elevated stresses can occur in pillars around the perimeter of a benched area. However, the existence of reduced stresses in the partially benched pillars seems to be in conflict with the field observations, which indicate that elevated stresses exist in the partially benched pillars. Nearer inspection of the model results show that stresses are not symmetrically distributed within pillars at the edge of a benched area, shown in Figure 8. It can be seen that zones of high stress exist within the partially benched pillar that are absent in the perimeter pillar, although the average vertical stress in the two pillars may be similar. The elevated local stresses are likely to contribute to the failure observed in the partially benched pillars in operating mines.

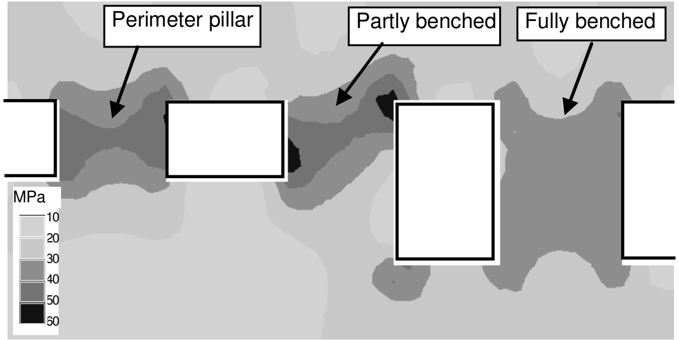

Figure 8. Section through the central part of an Examine 3D model showing maximum principal stress contours in and around pillars at the edge of bench mining. Contours in MPa.

4 CASE STUDY OF BENCHING-RELATED INSTABILITY

4.1 *Observed Instability*

Pillar instability was observed adjacent to an area of bench mining at a mine that is extracting a near horizontal limestone bed. Spalling of the pillar ribs, resulting in hourglass formation, was observed. In the area of concern, the pillars were square with side dimensions varying between about 12.2 and 15.2 m and were initially benched to 15.8 m high. Further benching was carried out, which increased the pillar height to 27 m. The room width was measured to be about 16.4 m, and the depth of cover is 140 m. The average pillar stress is about 15 MPa, based on the tributary area method. However, the irregular pillar shapes and effects of benching resulted in variable stresses in the pillars. The width to height ratio of the benched pillars was as low as 0.44 in the 27 m high area. Figure 9 shows a plan of the mine

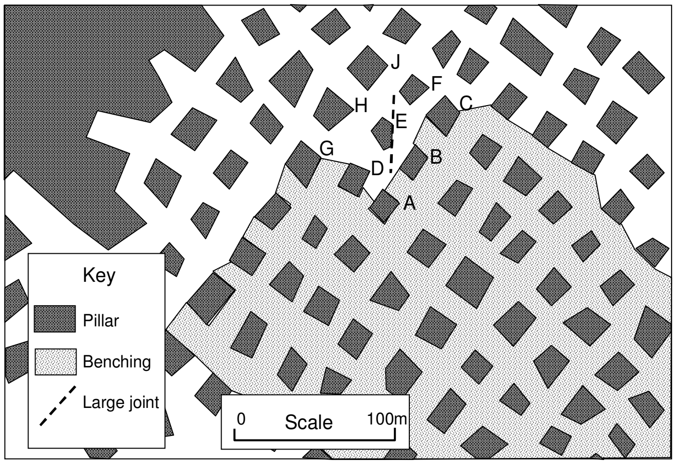

Figure 9. Plan view showing layout of pillars and bench mining at case study mine as modeled using the Examine 3D software.

workings indicating the area in which benching was carried out to a height of 27 m.

The limestone formation in this mine has uniaxial compressive strength in the range of 200-250 MPa. Jointing is near vertical with an average spacing of about 50 cm. A survey of joint orientations in the area showed that the main joint set strikes in the North-South direction. A single large, near vertical joint, was observed in the roof adjacent to Pillar E, and is shown Figure 9. Joint surfaces are rough, and the joint continuity is less than 3 m. Bedding joints are poorly developed and did not appear to affect the pillar stability. The rock mass rating (RMR) for this area was determined to be 78 as shown in table 4.

Table 4. Rock Mass Rating parameters in vicinity of unstable pillars at case study mine.

Parameter	Value	Rating
Intact rock strength	150 MPa	14
Joint frequency	2.0 joints/m	21
Joint condition	Rough joints with no infill, poorly developed bedding, joint walls unaltered	28
Groundwater	Dry	15
	Total:	**78**

The initial development mining was carried out about 15 years ago, but the final benching stage was carried out less than 5 years ago. A number of pillars were reported to be progressively spalling to the current hourglass shape at the perimeter of the benched area. Figure 10 shows the conditions of pillars B and E. Evidence of fracture through intact rock and slab formation was seen. Pillars A, B, D and E showed open vertical fractures and there were large slabs lying on the mine floor around the pillars. Pillar E was considerably reduced in size, owing to the presence of the large joint that intersected one of its corners and caused the corner to slough. The remaining part of the pillar was in a poor condition, containing many stress related fractures and slabs. Pillars C, F, H and J were in a relatively good condition and did not show any signs of stress damage.

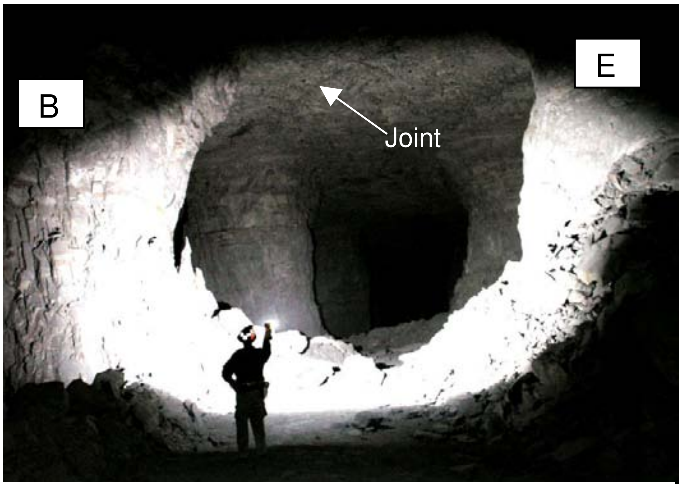

Figure 10. View of pillars showing slabbing and rubble from rib failure, Pillar B on left and Pillar E on right in photograph.

4.2 *Analysis and Discussion*

The pillars labeled A, B, D and E in Figure 10 are clearly exposed to elevated loading. Spalling to an hourglass shape, open fractures and slab formation are all well known manifestations of pillar overload. A 3D model of the area was set up using the Examine 3D software. The model simulated an area of about 300x300m with the pillars in question located near the center of the model. Two stages were modeled. The first stage simulated a condition prior to bench mining and the second simulated the benched configuration shown in Figure 9. The results showed that prior to bench mining, pillars D, E and F were slightly more stressed than the surrounding pillars owing to their smaller size. The stress distribution in the pillars after benching is shown in Figure 11. It can be seen that pillars D, E and F contain the highest stresses and A, B and C have already been partly relieved of stress by the bench mining. Pillar E carries the highest stress, because it is smaller than the other pillars, and is stiffer than the partially benched pillars. The relatively lower stresses in pillars A, B and C is expected, since their height has been increased by benching, and they have shed stress. However, as benching approached these pillars, the stresses will have been elevated and is likely to have caused the observed damage. The benching configuration, which forms a protruding right-angle, also contributes to the elevated stresses on these pillars.

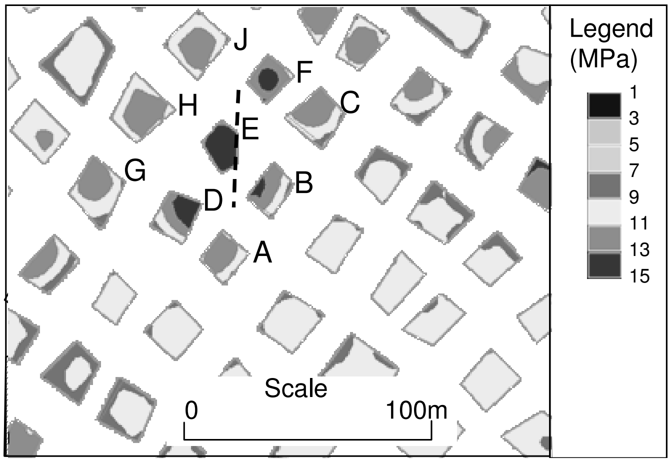

Figure 11. Examine 3D results showing contours of maximum principal stress in the pillars.

5 SUMMARY AND CONCLUSIONS

Observations show that floor benching can cause instability of pillars at the perimeter of bench mining operations. Instabilities can be caused by the geological structures in the rock and by an increase in pillar loading.

The presence of large inclined joints or other geological discontinuities can cause instability because they are more likely to be exposed by the increased height of pillars.

An increase in pillar loading can be explained by considering the pillar stiffness. The benched pillars have a reduced stiffness and will shed load onto the stiffer development pillars. The numerical models showed that there was an increase in stress of about 15% in the pillars around the perimeter of the benching operations.

The models also showed that the strength of a pillar is reduced in a near linear manner as each side of the pillar is bench mined. The net effect is that partly benched pillars experience a simultaneous reduction in strength and load.

The instability of the partly benched pillar can be further ascribed to the uneven distribution of stresses within the pillars when they are located at the edge of a benching operation. High local stresses near the top and bottom of the pillar can initiate stress spalling.

The case study confirmed that increased stresses exist within pillars at the perimeter of the bench mining operations. It was further shown that irregular sized pillars are more likely to become unstable during bench mining. The smaller pillars are more susceptible to stress increases as benching approaches. The case study also showed that the benching should advance in a straight line, to avoid lagging corners that will result in elevated stresses in the perimeter pillars and degrade their stability.

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