Massive Pillar Collapse: A Room–and–Pillar Marble Mine Case Study

Sandin E. Phillipson, Geologist
Roof Control Division MSHA
Pittsburgh, PA

ABSTRACT

The Mine Safety and Health Administration's Roof Control Division responded to a massive ground failure at an underground marble mine in northern Georgia. The ground failure occurred in a benched area that had been abandoned in the early 1990s. It involved the failure of an estimated 19 pillars, in conjunction with a massive roof fall of an undetermined extent that was at least 60 ft high. Pillars in the benched area had been mined nominally 40 x 40 feet to a height of 50 feet ft, with 40-ft mining widths, although it seems likely from measurements and accounts from mining personnel that pillars were even smaller than intended. Average overburden depth was 500 ft, and the rock mass was characterized by three sets of intersecting geological discontinuities that not only defined very blocky conditions that were conducive to pillar spalling and volume loss, but they were also adversely oriented in such a way as to cut diagonally through pillars at a high angle.

The recently released S-Pillar software from NIOSH was used to determine pillar safety factors in the failure area and indicated that pillars were undersized for the conditions. S-Pillar was used to assess pillar stability in active areas to evaluate the likelihood of experiencing similar collapses in the future. S-Pillar correctly identified the pillars in the bench area as having been at risk for instability, in light of their ultimate failure. A two-dimensional finite element model was used to evaluate the possible stages of failure and to assess the likelihood of continued failure in the benched area that might affect more distal mine openings. Although stone mines are generally characterized as having more forgiving conditions than those found in softer sedimentary rocks, the failure shares some characteristics with domino-style massive pillar collapses experienced in coal and trona mines. First, the minimum dimension of the benched area approached 350 ft; second, the pillars defined by benching had small width-to-height ratios (0.8), and; third, the pillar failure area was slightly greater than 4 acres.

The massive pillar collapse and associated roof fall illustrate the importance of incorporating pillars that have been properly sized for depth and for the final bench height. Furthermore, the designed dimensions must be adhered to during the actual mining process. Finally, the importance of understanding the geological conditions and their effect on the rock mass is critical.

INTRODUCTION

On September 21, 2011 at 3:45 a.m., employees on the surface at an underground marble mine located in northern Georgia felt what they thought was a shot being fired underground. Shortly thereafter, it was found that a portable toilet inside the mine and a tag-in board outside the portal had been knocked over by an apparent air blast. Further investigation revealed that a massive roof fall had occurred in the benched area of a portion of the mine that had been abandoned in the early 1990s. Fortunately, the massive collapse resulted in no injuries. Following notification of the Mine Safety and Health Administration (MSHA), personnel from the Southeastern Metal and Nonmetal Safety and Health District conducted a traverse around the perimeter of the failure area and determined that up to 19 pillars had collapsed amidst a massive roof fall. Although such domino-style pillar collapses have happened in coalmines (Mark, Chase, and Zipf, 1997) and trona mines (Swanson and Boler, 1995), the extent of failure that occurred at the study mine is almost without precedent in stone mines (Dismuke, Forsyth, and Stewart, 1994), which are commonly characterized by relatively forgiving environments due to high rock strengths. The height of the roof fall was later confirmed by drilling from an upper level to be at least 60 ft, although the maximum height and extent of the roof fall is unknown. The pillar failure encompassed a rectangular area 300 ft in width by 600 ft in length. The width may be considered to be larger if an additional row of pillars that is exhibiting signs of failure is included.

Because of the large pillar failure area, the possibility that failure might continue to propagate into active portions of the mine and the possibility that similar failure might be encountered in newer areas of the mine that had been planned to incorporate benching, MSHA Technical Support conducted an evaluation of the failure mechanism and ground conditions in various parts of the mine. Measurements of dimensions, strata orientation, and structural discontinuities were obtained for incorporation into the NIOSH S-Pillar software program (NIOSH 2011), as well as a staged finite element model using $Phase^2$ (Rocscience, Inc. 2011). These models were used to assess the mechanism and progression of the failure, evaluate pillar stability in old and new workings, and evaluate the likelihood of continued failure in old and new areas. This case study validates the use of S-Pillar to evaluate stability in underground stone mines, highlights the importance of understanding the effects of structural discontinuities on pillar stability, and reinforces the need to adhere to the designed pillar dimensions to maintain stability.

BACKGROUND

The subject mine is one of several underground room-and-pillar mines that extract marble in an area approximately 50 miles north of Atlanta, Georgia (Figure 1). The mines are developed in the Cambrian-aged Murphy Marble, a formation within the Murphy Belt, which predominantly contains marble and schist with lesser amounts of quartzite and meta-conglomerate. These metasediments were originally deposited in a stable region as conglomerate, sandstone, shale, and calcic and dolomitic limestone (Graham 1969). Following deposition in the Cambrian, deformation occurred near the end of the Ordovician (as a result of the Taconic Orogeny) and again at the end of the Pennsylvanian (as a result of the Alleghanian Orogeny) (Graham 1969). The Murphy Belt, representing a tightly folded, overturned syncline, trends northeast from northern Georgia into southwestern North Carolina and includes, from oldest to youngest, the Nantahala, Brass town, Murphy, Marble Hill Hornblende Schist, and Andrews Formations (Fairley 1969). Later interpretations of the stratigraphy differ by including quartzite units (Tusquitee Quartzite and Nottely Quartzite) of formation rank in the sequence (Power and Forrest 1973; Groszos 1986). Although the sequence of lithologic units is agreed upon by previous studies, the assignation of those units to formal formations has been confusing and inconsistent (Power 1976). The Murphy Marble is interpreted by Power and Reade (1973) and Groszos (1986) to represent a carbonate bank. Near the study mine, Fairley (1969) and Power (1976) interpreted the Murphy belt to have been folded into an overturned syncline, and the marble interlaces with and passes laterally into the schist of the Andrews and Brass town Formations (Power and Reade 1973).

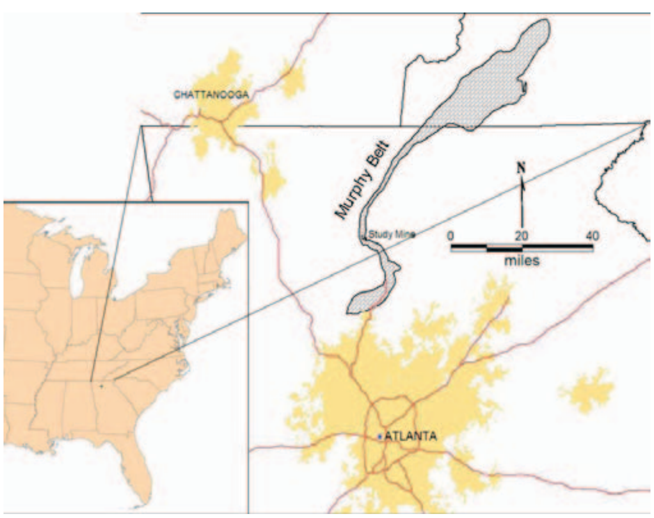

Figure 1. Location map showing position of study mine relative to the extent of the Murphy Marble in northern Georgia and southwestern North Carolina.

The subject mine is located in the informally named Whitestone Belt, one of three discontinuous pockets of marble that occur within the Murphy Belt (Power 1976). The Whitestone Belt is overlain by the quartz-biotite schist of the Brass town Formation, substantiating interpretations that the marble occurs on the overturned limb of a syncline (Power 1976). The marble is divided into an upper (actually lower in the stratigraphic sequence because of overturning), medium- to fine-grained dolomitic marble and a lower, coarse-grained calcite marble. The dolomitic marble is in contact with the overlying quartz-biotite schist, which hosts many thin layers of talc-phlogopite schist (Power 1976). The main body of the unit is massive, fine-grained dolomite marble that is 500–600 ft thick but may have been repeated due to faulting. Along the two-mile outcrop of the Whitestone Belt, eight random room-and-pillar mines had been developed by 1976, using lateral mining dimensions of 38–64 ft (Power 1976). Bench heights in older workings reached 150 ft, but, by 1976, ultimate mining heights had been reduced to 65 ft (Power 1976).

The strike and dip of the formation in the northern Georgia marble mining district is variable, but marble banding along the Whitestone Belt generally trends N 05° W and dips toward the east from as little as less than 10° to as much as 30°. This local northerly trend is significantly different from neighboring legs of the Murphy Belt, which trend northeast and southeast, respectively. Where the marble bands dip less than 10°, mine workings appear very similar to a standard limestone mine that would be characterized by a relatively horizontal roof horizon. Where the dip increases, mining levels at this and other northern Georgia marble mines are arranged in a series of horizontal stair-steps that may partially overlap as the levels follow the formation to depth. In these examples, although mining levels remain horizontal, the roof horizon is commonly characterized by a saw-toothed profile, defined by intersecting partings and joints that define hanging wedges. Because of the propensity for these wedges to drop out of the roof despite scaling, at least one area marble mine performs routine pattern bolting to ensure that the wedges are supported. Bolting is not, however, performed at the study mine.

The mine extracts marble for its calcium carbonate content by the regular room-and-pillar mining method on multiple levels, generally stepping gently downward toward the east. The mine is characterized by a prominent “dog leg” where the marble formation changes strike and dip, associated with a change in ground conditions and mining layout (Figure 2). Initial mining, characterized broadly as random room-and-pillar, was conducted on the 1,070-ft level, which represents the elevation above sea level at outcrop in the valley. In the northern half of the mine (that area north of the hinge point in the dog leg), regular room-and-pillar mining was conducted on the 920-ft level and the 880-ft level, stepping down toward the east with the dip of the marble. This area had been abandoned in the early 1990s, although ramps are being developed to the 720-ft level to continue to follow the formation down-dip. In the southern half of the mine, regular room-and-pillar mining was conducted on the 890-ft and 820-ft levels, which are superimposed because of the very low dip angle of the formation, representing the current active mining horizons. The collapse occurred in the 920-ft level, which had been mined in the 1980s and subsequently benched in the central area in the late 1980s to early 1990s. The original mining height was planned for 25 ft, and the ultimate benched height was 50 ft. Mining dimensions are defined by pillars designed 40 x 40 ft with 40-ft mining widths. Actual mining widths were generally measured as 42–43 ft.

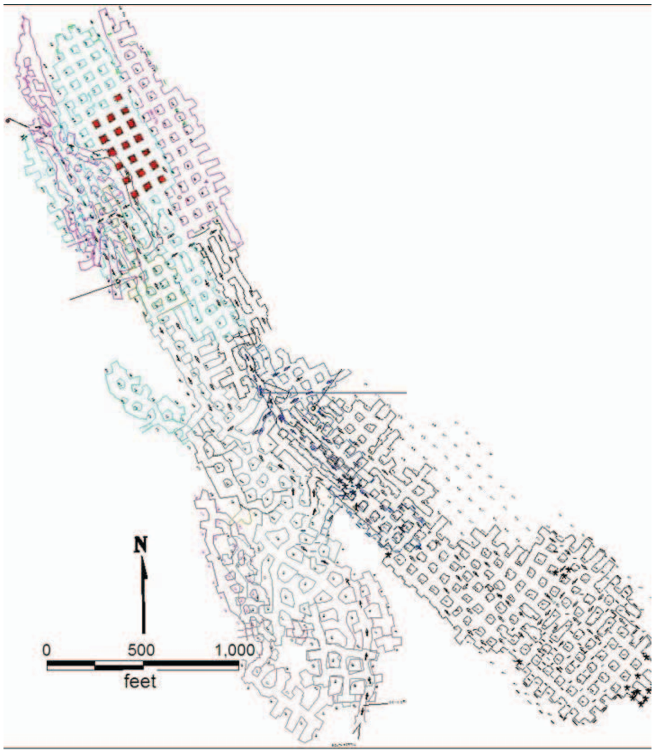

Figure 2. General mine map, showing extent of pillar failure area (red) in relation to the rest of the mine. Prominent "dog leg" represents change in strike and dip of the marble deposit, and coincides with a change in ground conditions.

METHODOLOGY

Measurements of the strike and dip of structural discontinuities, as well as their spacing, were collected in different parts of the mine using a standard Brunton hand transit and tape measure. Measurements of mining dimensions were obtained in the mine using a laser range meter and compared to planned dimensions portrayed on digital mine maps. Observations were conducted at the margin of the collapse area and in the active mining area. The condition of the roof and pillars was assessed in various parts of the mine. These values were used for performing evaluations of pillar stability with the NIOSH S-Pillar program (Table 1) and used for input parameters in the Phase^2 (Rocscience, Inc. 2011) finite element modeling program (Tables 2 and 3). Fifteen thousand psi represents the default value for unconfined compressive strength in S-Pillar, a program based on case studies of limestone mines. A marble mine in the same formation, within approximately five miles of the study mine, reported that core samples of the deposit exhibited UCS values of 12,000 psi, considered low for the marble as a whole. Thus, the 15,000-psi value is considered reasonable and may, perhaps, even be generous. Input values in Phase^2 are based on published values for a range of samples since actual geotechnical data were not available for this specific mine.

Pillar safety factors were determined with S-Pillar for the collapse area and compared to the current active mining area. The sequence of mining, benching, and pillar collapse was represented in Phase^2 in a series of staged excavations. Pillars were removed in the model to simulate their failure. The eastern-most pillar was removed first, based on recollections of mine personnel who stated that those pillars exhibited sloughing shortly after benching and on their portrayal on mine maps as being noticeably undersized compared to the neighboring pillars.

Table 1. Input values used to assess pillar stability in the collapse area with S-Pillar at the study mine.

Parameter	Value
Pillars	Square
Heading Centers	80 ft
Heading Width	40 ft
Crosscut Width	40 ft
Development Height	25 ft
Benched Height	50 ft
Maximum Cover Depth	500 ft
Unconfined Compressive Strength	15,000 psi
Large Discontinuities?	Yes, spaced 30 ft, dip 60°

OBSERVATIONS

Observations in the collapse area were conducted at the southern and western margin of the benched area (Figure 3). At the southwestern margin of the benched area, the west sides of the pillars are 25 ft high where benching ceased but are 50 ft high on the east side, where they have been exposed by benching or where a ramp had been driven onto the 920-ft level (Figure 4). The roof of the drift, even at the margin of the collapse area, was extensively damaged with what appeared to be recent small falls of rock, accompanied by pillar sloughing, based on the bright, fresh surfaces exposed in contrast to the dark soot coloration on areas that had remained intact for a long period of time. In this area, the contorted marble beds strike approximately N 05° W and dip up to 20° E. Prominent, iron-stained joints strike parallel to the marble but dip perpendicularly to marble banding (N 10° W, 63° W). A second, less prominent joint set strikes N 65° W and is oriented vertically.

The roof fall material consisted of very large, angular blocks and slabs (6-10 feet long) that were piled up above the 50-ft high roof line, obscuring any pillars that might have remained in the interior of the fall rubble (Figure 5). The lip of a very large fall cavity was visible in the roof, although the top and inside surfaces could not be discerned because of condensation in the air that obscured long-distance vision. The large blocks were jagged-edged and did not generally exhibit flat surfaces that would be indicative of unraveling along joints. Instead, the blocks' jagged edges were suggestive of failure by bending stress.

Farther west from the fall, on the unbenched portion of the 920-ft level, pillars were observed to respond to additional abutment loading resulting from the massive collapse. All pillars in these rows over a distance of eight crosscuts were characterized by prominent, dipping joints that strike parallel to marble banding but dip diagonally through the pillars from corner to corner (Figures 6 and 7). The pillars exhibited freshly spalled surfaces along the joint traces, and the joints exhibited open apertures even in the center of the pillar. Some joints appeared to have a milled, rubble-like appearance that is suggestive of shearing. The damage observed in the 25-ft-high pillars is suggestive of additional abutment loading resulting from the adjacent, massive collapse.

Table 2. Input values for rock properties used to assess collapse area with Phase2 at the study mine.

Parameter	Value
Initial Element Loading	Field stress and body force; 1:1 ratio of horizontal to vertical stress
Poisson's Ratio	0.3
Young's Modulus	432,000,000 psf
Failure Criterion	Mohr Coulomb
Material Type	Plastic
Tensile Strength	345,000 psf
Peak Friction Angle	35°
Peak Cohesion	400,000 psf
Dilation Angle	10°
Residual Friction Angle	30°
Residual Cohesion	40,000 psf
Residual Tensile Strength	28,800 psf
Unit Weight	165 pcf

Table 3. Input values to describe geological discontinuities affecting the rock mass for evaluating collapse area with Phase2 at the study mine.

Parameter	Value
Marble Banding Partings	
Slip Criterion	Mohr Coulomb
Tensile Strength	0 psf
Peak Cohesion	23,000 psf
Peak Friction Angle	30°
Normal Stiffness	600,000 psf/ft
Shear Stiffness	600,000 psf/ft
N 05° W, 65° W Joints	
Slip Criterion	Mohr Coulomb
Tensile Strength	0 psf
Peak Cohesion	15,000 psf
Peak Friction Angle	28°
Normal Stiffness	400,000 psf
Shear Stiffness	400,000 psf
N 05° W, 90° Joints	
Slip Criterion	Mohr Coulomb
Tensile Strength	0 psf
Peak Cohesion	23,000 psf
Peak Friction Angle	30°
Normal Stiffness	600,000 psf/ft
Shear Stiffness	600,000 psf/ft

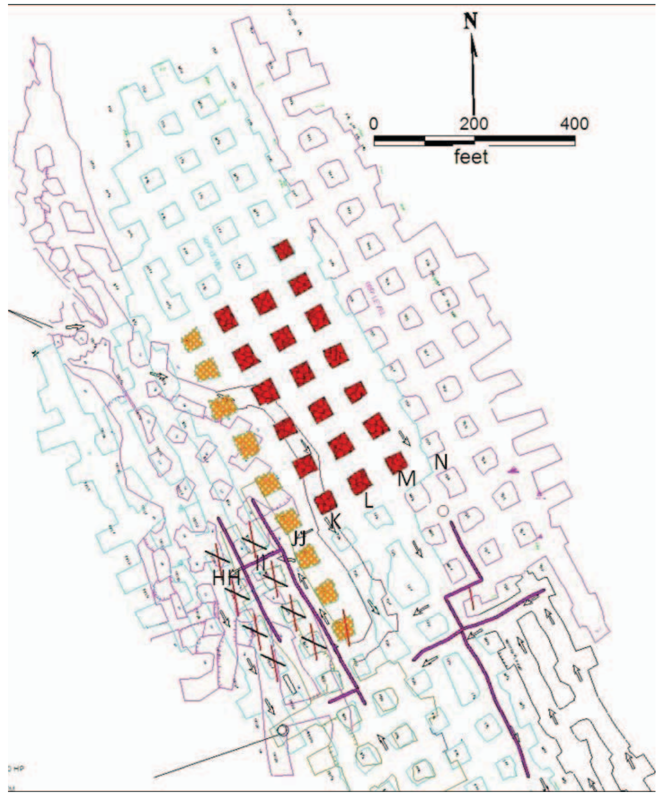

Figure 3. Map of collapse area, showing observation traverse (heavy purple line) and damaged pillars (red = believed to have failed; orange = taking weight, exhibiting degradation). Red lines represent prominent, iron-stained joints; black lines represent joints. Collapse was localized to the benched area of the 920-ft level, shown in light blue.

Figure 4. The row of pillars at the margin of the benched area is characterized by extreme degradation, with the eastern portions (facing the benched side) 50 ft tall and exhibiting failure along pre-existing geological structures.

Figure 5. Roof fall debris is composed of very large blocks. The photo vantage point is approximately 40 ft from the rubble.

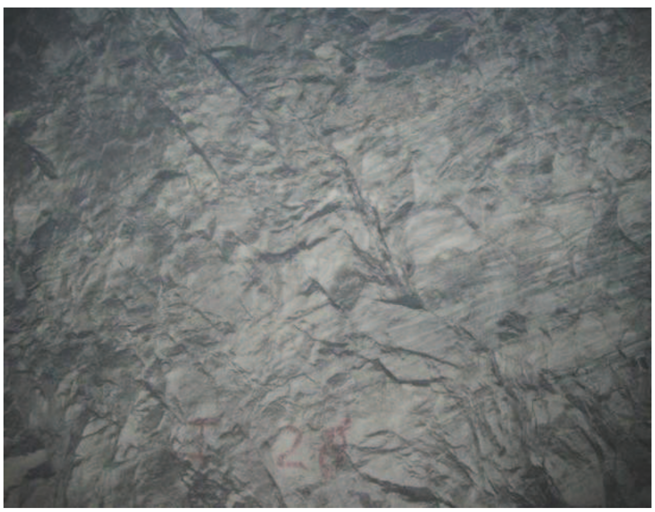

Figure 6. Open-aperture joint, which strikes N 10° W and dips 63° W, is located in the center of pillar II28. This orientation of joints typically runs diagonally from corner to corner in the JJ, II, and HH pillars. White outline represents close-up shown in Figure 7.

Further assessment was performed in adjacent areas of the 920-ft level where active haulage ways were defined and in the southern area of the mine where active mining was being conducted, in order to ascertain whether widespread collapse should be a prevailing concern in this mine. Observations in those areas indicated that the quality of the ground was much better than in the collapse area. There appear to be two main reasons for this, both of which are reflections of the geological conditions. First, the set of joints that strikes N 05° W and dips approximately 65° W, thereby dissecting pillars diagonally, is not present south of the collapse area. Therefore, it appears that this joint set exerts a particularly deleterious effect on ground stability when present. This diagonally crosscutting joint set is not only in the most unfavorable orientation for pillar stability but is also generally characterized by

Figure 7. Close-up of Figure 6, showing open aperture along joint that penetrates deeply into the pillar. This feature contrasts with the irregular, localized nature of small fractures that represent blast damage on the pillar skin.

heavy iron staining, indicating open apertures that easily transmit water and offer little to no cohesion between opposing blocks of rock. Second, a change in dip, from up to 20° in the collapse area to less than 10° in the southern, active area results in a more stable roof horizon that is not characterized by a sawtooth profile of intersecting joints. It is interpreted that the sawtooth profile makes it easier for progressive raveling to occur, especially since the mine does not install rock bolts. Although the southern area hosts abundant, closely spaced (10–24 in.) vertical joints that strike N 65° W, they do not exhibit open apertures, and pillars exhibited virtually no evidence of spalling (Figure 8).

Figure 8. Typical condition of pillars on the 820-ft and 890-ft levels, showing an absence of open-aperture joints or evidence of raveling.

DISCUSSION AND ANALYSIS

S-Pillar

The 920-ft level collapse area shares several similarities with the circumstances of domino-style cascading collapses in coalmines. These types of collapses are commonly characterized by wide panels (350 ft) that encompass more than 4 acres. (The study mine's collapse area encompassed 4.1 acres.) In these collapses, tall, slender pillars (those with a small width-to-height ratio) had been developed (Mark, Chase, and Zipf 1997). It is interpreted that those were finely balanced systems and that the failure of only a single pillar was enough to shed load onto surrounding pillars, precipitating a cascading, rapid failure. Research performed by NIOSH on stone mine pillar performance identified two main factors in predicting pillar instability: 1) width-to-height ratio of 0.8 or less and 2) safety factors of 1.8 or less (Esterhuizen, Dolinar, and Ellenberger 2008; Esterhuizen, Dolinar, and Ellenberger 2011; Esterhuizen, Dolinar, Ellenberger, and Prosser 2011) (Figure 9). Pillar stability was further influenced by the spacing and orientation of planar geologic discontinuities. Pillars in the failed 920-ft level were 50 ft high and 40 x 40 ft, defining a width-to-height ratio of 0.8, cut by high-angle joints that further degraded the strength of pillars that only had a safety factor of 1.1 as calculated by S-Pillar.

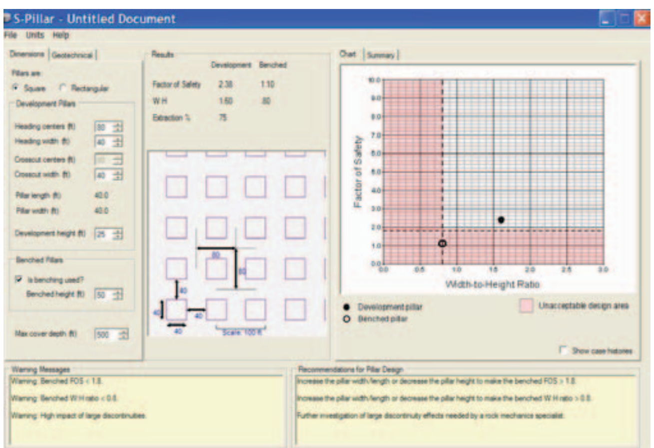

Figure 9. Analysis of pillar design on the 920-ft level using NIOSH S-Pillar software for limestone mines. Benched pillars on 920-ft level are solidly outside the acceptable design category, with a safety factor calculated by S-Pillar of only 1.1.

Mine personnel stated that the M row of pillars in the benched area had exhibited signs of degradation shortly after benching, prompting the abandonment of the area in the late 1980s or early 1990s. Other mine personnel suggested that the back horizon may have encroached upon or even reached the contact with the overlying quartz-biotite schist which, especially in combination with the previously reported talc layers, could have represented a large potential delamination plane. The mine map portrays the M pillars as smaller than the nominal 40 x 40 ft dimensions, which results in an even lower width-to-height ratio and lower safety factors. It is, therefore, interpreted that failure initiated in the M row and that, as those pillars failed, their loads were transferred onto the adjacent, meta-stable benched pillars, which failed in succession. Because the area had been abandoned for many years, the relative timing of pillar failure and roof failure is unknown. Measurements in adjacent areas indicated that mining widths were generally several feet larger than the nominally planned 40 ft, resulting in corresponding pillar dimensions several feet smaller than 40 x 40 ft. Thus, the pillars are likely to have actual width-to-height ratios and safety factors that are even smaller than would be indicated for the planned dimensions.

Conditions in the southern, active mining areas appear much better than in the collapse area. The marble exhibits a very low-angle dip so that it is nearly horizontal, greatly reducing the occurrence of wedges in the back. Further, the N 10° W, 65°W joints that represent planes of preferential weakness and negatively influence pillar stability in the north are absent. The 890-ft level is not intended to ever be benched because of the 43-ft sill thickness to the underlying 820-ft level. NIOSH S-Pillar software indicates that for the current 25-ft development height, pillars should display acceptable width-to-height ratio (1.5) and safety factor (2.39) values. The lower, 820-ft level, is intended to be benched. Even though ground conditions appeared good during the underground evaluation, the S-Pillar analysis indicates that, when benching is performed, the resulting pillars will be on the margin of acceptable design (Figure 10). The S-Pillar software illustrates the importance of pillar dimensions used in the pillar strength calculations to determine the pillar safety factor. The software indicates that a 40 x 40 x 50-ft pillar is on the margin of acceptable stability, and the mine must recognize the importance of adhering to the designed dimensions. Despite the intention to mine pillars 40 x 40 ft, with 40-ft mining widths, the widths measured were generally 42–43 ft. The S-Pillar analysis indicates that this loss of pillar volume would be sufficient to transition the resulting benched pillars out of the acceptable design field, as the pillar safety factor is reduced from 1.87 to 1.62.

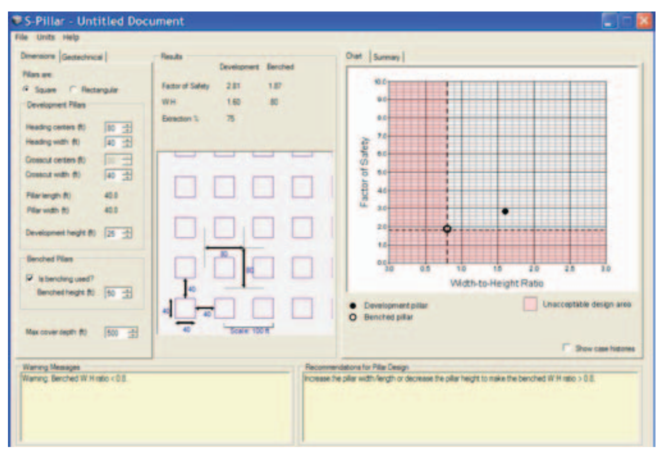

Figure 10. NIOSH S-Pillar analysis results for benching on the 820-ft level, showing marginal but still acceptable stability.

Finite Element

Observations suggest that the JJ, II, and HH pillars (labeled in the following diagrams) are being subjected to excessive loading. The JJ pillars, which are adjacent to the 50-ft benched area, could fail. Thus, large-scale collapses could continue in the northern area as remaining pillars are, in effect, removed. A finite element modeling program was used to assess the possible progression of failure, and the possible consequences of continued failure (Figures

11a-f). The two-dimensional model, which treats square pillars as strip pillars, incorporated major geologic discontinuities, including partings along dipping marble beds (inclined 20°), vertical joints, and 65° dipping joints that dissected pillars as ubiquitous joints. In the model, strength factors (equivalent to a safety factor for model elements but calculated differently from the safety factors discussed in terms of S-Pillar) for elements in the K, M, and N pillars were reduced to less than 1 immediately upon benching the 920-ft level (Figure 11b). It should be recognized that the model results should be interpreted only as stability trends, rather than absolute values. At this stage, the model suggests that both the M and K pillars are affected by elements with safety factors less than 1.

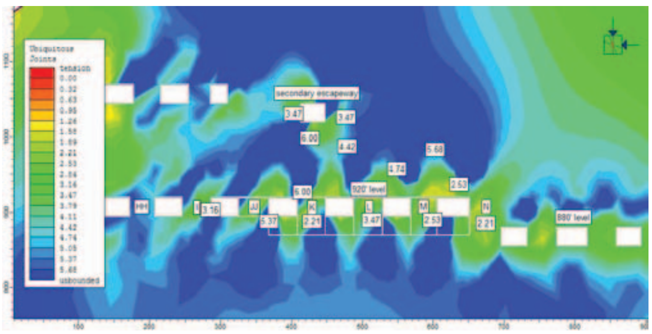

Figure 11a. Distribution of safety factors with development only on the 880-ft and 920-ft levels. Pillar rows are annotated as referred to in the text. Box in upper right portrays orientations of geologic discontinuities incorporated in the model, based on field observations.

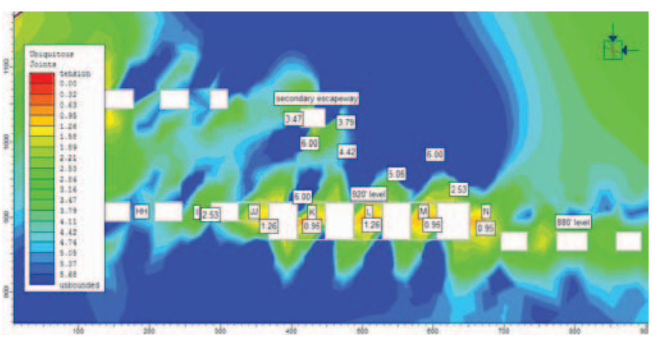

Figure 11b. Distribution of safety factors following benching of the 920-ft level to 50-ft height. Note the significant reduction of element safety factors in benched pillars compared to Figure 11a.

However, the M pillar was chosen as the first pillar row to fail based on smaller-than-planned dimensions on the mine map, and statements from mine personnel indicating that the M pillars had been subject to constant raveling, interpreted as a sign of taking weight, possibly from cantilevering beneath the quartz-biotite schist delamination horizon. Following the loss of the M pillar, interpreted as the most likely to have failed in the benched area, elements in the L pillar also exhibited safety factors of less than 1, and safety factors began to exhibit a marked decrease in the roof of the resulting unsupported area (Figure 11c). With the loss of the L pillar, safety factors in the K pillar were drastically reduced, and safety factor values less than 1 propagated high into the roof, indicating the onset of the large roof fall that occurred (Figure 11d). As failure progressed to include the loss of the K pillar, safety factor values in the JJ pillar were reduced to less than 1, and two arcs of low-value safety factors were shown developing high into the roof, similar to a pair of closing pincers (Figure 11e). Figure 11e represents the observed state of the ground at the time of the investigation, with a large roof fall having developed above the failed pillar area, the JJ (and likely also the N) row of pillars taking weight, and a large reduction in safety factor values for elements in the II pillars. The model results tend to be substantiated by the presence of open joints and freshly spalled surfaces observed on the JJ, II, and HH pillars. It should be recognized that pillars need not have toppled over or collapsed completely in order to represent a state of failure. Instead, it is more likely that the pillars would have gradually crushed out, deforming after a style of strain-softening as incremental movement occurred along numerous joint planes. Most of the pillars likely retained some low level of residual strength and could even exist as remnants among the roof fall debris. However, the pillars are considered to have failed when that residual strength was no longer equal to the axial stress imparted from the weight of the overlying rock mass. With the expected continued destabilization and eventual failure of the JJ pillar, the model indicates the potential for an enlargement of the ground collapse area in the roof so that, even a secondary escape way, prudently abandoned, would be encompassed by safety factor values less than 1, despite being located 100 ft above the roof of the collapse area (Figure 11f).

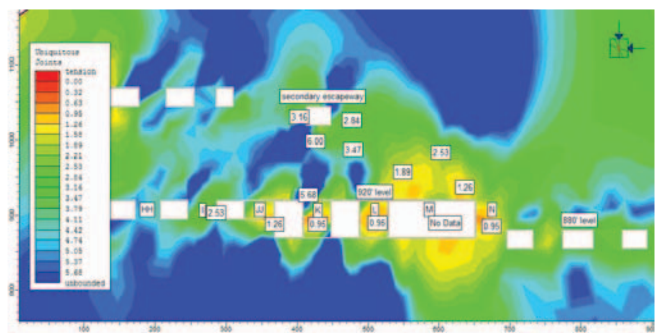

Figure 11c. Distribution of safety factors following the loss of the M pillar, interpreted to have been the first to fail based on mine personnel accounts.

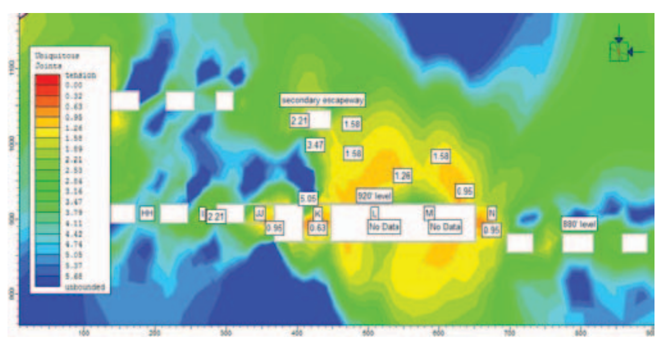

Figure 11d. Distribution of safety factors following the loss of the L pillar.

CONCLUSIONS

The MSHA Technical Support, Roof Control Division conducted an assessment of ground conditions at the study mine in order to better understand the causes of a massive collapse in an abandoned area and to determine whether the active mining levels might be subject to the same potential for collapse. Underground observations indicate the geological conditions are different in the abandoned, collapsed area compared to the active areas. At this time, the potential for pillar failure in the active portions of the mine, on the 820-ft and 890-ft levels is low. This is mainly because of more favorable geological conditions characterized by an absence of the N 05° W, 65° W joints and a moderation of the marble dip to less than 10° that resulted in elimination of the heavily jointed, sawtooth roof profile.

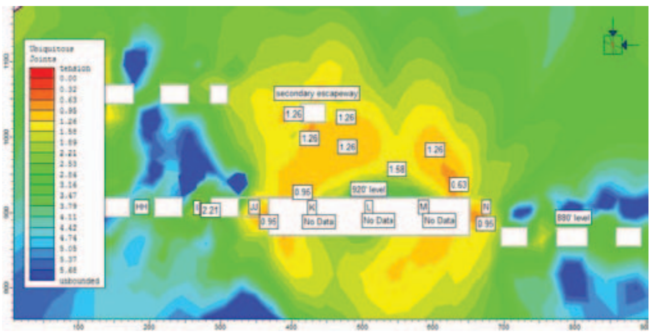

Figure 11e. Distribution of safety factors following the loss of the K pillar. The distribution of low-value safety factors generally mirrors the shape of the large roof fall cavity that was observed during the underground investigation. Note the low safety factors affecting the JJ pillar, which is substantiated by field observations as indicated in Figure 4.

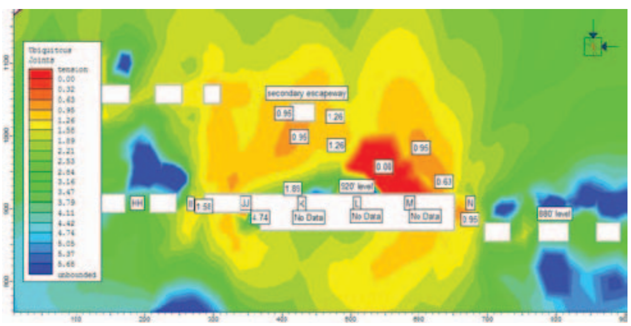

Figure 11f. Distribution of safety factors following potential, but likely, loss of the JJ pillar. With the loss of the JJ pillar, the potential ground collapse area expands to encompass the former secondary escapeway, located approximately 100 ft above the 920-ft level. Safety factor values in the II pillar have been greatly reduced, as substantiated by field observations as indicated in Figures 6 and 7.

Analysis of the collapse and active areas appears to validate the effectiveness of the NIOSH recently released S-Pillar software for evaluating pillar stability in stone mines. Although the case study database is based on limestone mines, the marble in this instance appears to have similar enough properties that actual failures occurred as would have been indicated by very low S-Pillar safety factors. Because S-Pillar has essentially been calibrated to the site-specific conditions at this mine by being able to back-analyze an actual collapse, S-Pillar results should be carefully considered when designing bench heights in future mining areas.

It must also be noted that actual mined dimensions should be the same as designed dimensions. Mining widths of 43 ft, resulting from blasting over break of 1.5 ft on each of the four pillar sides, translates into a pillar that is 37 x 37 ft rather than 40 x 40 ft. This is 14% smaller than intended. If pillars are already designed to meet only the minimum stability value, to allow maximum recovery, this 14% could represent the difference between stability and failure when combined with other unexpected circumstances that may adversely affect pillar quality. In addition to adhering to designed dimensions, the effect of depth and associated axial load must also be recognized when following a dipping horizon. A traditional design that has been used for many years could be found to be inadequate at greater depths.

Finally, the importance of understanding the effect of geological discontinuities cannot be overstated. Rock strength may mean little when the rock mass is characterized by several intersecting sets of closely spaced joints, particularly when joints are arrayed to cut diagonally through pillars.

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