Massive Pillar Collapses in U.S. Underground Limestone Mines: 2015–2021

Gregory M. Rumbaugh, Christopher Mark, and Todd Kostecki
Mine Safety and Health Administration

ABSTRACT
From 2015 to 2021, five massive pillar collapses occurred at four underground stone mines in the eastern United States. These events resulted in powerful airblasts that damaged mine infrastructure and mobile equipment, seriously injured miners, and disrupted underground travelways. Each of these pillar collapses propagated through the overlying strata, causing a subsidence basin on the surface. Pillar collapses are particularly hazardous for miners because they can occur with little warning and can affect miners that are far from the pillar collapse area. The following case studies show that certain factors may increase the likelihood of a pillar collapse. For instance, each of the five events involved the collapse of at least twelve benched pillars with width-to-height ratios (w/h) of 0.8 or less. This study elaborates on these factors and proposes a framework to assist mine operators where they identify similar hazards.

INTRODUCTION
A massive pillar collapse, also known as a cascading pillar failure, domino failure, or pillar run, occurs when an array of pillars, fail in quick succession (Mark et al. 1997). The collapsing ground and resulting airblast are hazardous to miners underground and on surface, and experience demonstrates they can occur with little overt warning (Mark and Rumbaugh 2022). This is especially the case for large underground limestone operations.

Currently, there are 100 active underground stone mines operating in 19 states as shown in Figure 1. Eighty-six of these mines extract crushed, broken limestone, while the remaining extract various crushed or dimensional stones. Underground stone mines can have a long mine life. For instance, stone mines can have areas mined over 10 years prior, with some having areas over 100 years old. Many of these legacy workings contain pillars that were not developed with modern pillar design methods, and have the added issues of weathering and age-related deterioration.

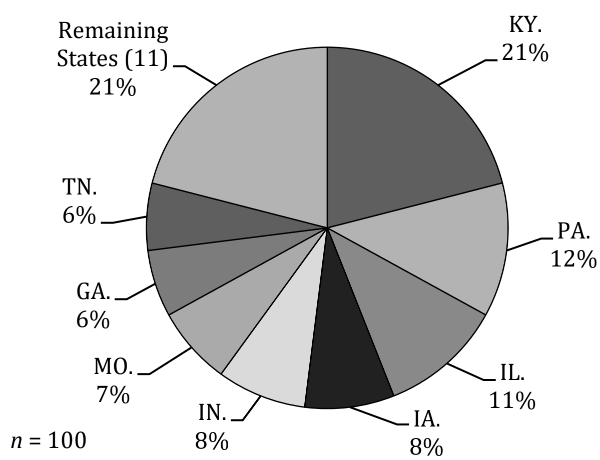


Figure 1. Active underground stone mines in the U.S. Metal mines, such as those extracting zinc, are not included.

A variety of engineering methods and modern design tools are available to guide the design of new pillars and evaluate the stability of existing stone pillars. One of the most widely used stone pillar design programs in the

United States is the S-Pillar software that NIOSH developed (Esterhuizen et al. 2011). S-Pillar derives its empirical database from studies at dozens of U.S. underground stone mines and is applicable for tabular, single seam, mining conditions with simplified pillar layouts. This software establishes two design criteria for pillar stability; the pillar should have a minimum Factor of Safety (FOS) of 1.8 and a minimum *w/h* (width-to-height ratio) of 0.8.

While limestone is typically a very strong rock, deposits contain joints and other geologic features that will impact pillar strength, especially slender pillars, where *w/h* is less than 0.8. Development of slender pillars occurs during secondary mining when bench mining the floor. Slender pillars are also sensitive to variations in pillar width that blast damage and overbreak can cause.

Since 2015, five massive pillar collapses occurred at four underground stone mines in the eastern United States. In three of the four mines, the pillar collapses occurred in legacy workings and were at least 15 years old. The pillar collapse areas in all five of the case studies contained pillars that did not meet the S-Pillar criteria.

CASE STUDIES

Mine A – April 2015, Pennsylvania

At approximately 5 AM, three underground miners were about to enter the portal to begin their shift when they heard what sounded like the firing of shots underground. An airblast then exited the portal with enough force to throw the miners and their equipment approximately 50 ft, injuring all three miners. Two of the miners were unconscious and required helicopter transport to the hospital. Significant subsidence occurred at the surface above the mine, displacing an area over seven acres (Figure 2). It was determined that these events were the result of a collapse of up to 35 pillars (Figure 3). Fortunately, no other miners were underground at the time of the pillar collapse and no other injuries occurred.

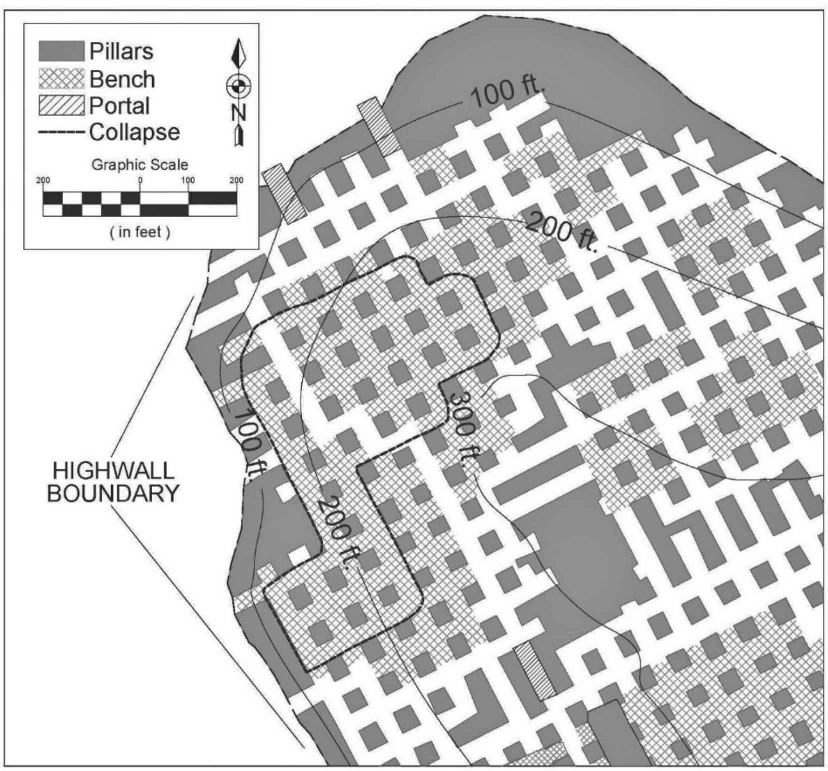
Figure 2. Aerial view of Mine A subsidence

The mine had operated for approximately 25 years. Mine maps showed that the collapsed pillars were some of the first pillars in the mine, and the mine operator benched the area approximately 15 years prior to the pillar collapse. Although the benched areas were inactive legacy workings, a travelway bisected the pillar collapse and served as an escapeway for miners.

The operator's state mining permit defined the rooms and pillars as 35-ft square on 80-ft centers. The limestone averages 60 ft in thickness, with mining planned in two lifts (i.e., initial development and benching). The height of the initial development was 23 ft. Secondary bench mining removed an additional 30 ft from the floor, resulting in a total planned mining height of 53 ft. Observations at the perimeter of the pillar collapse showed the actual mining dimensions deviated from planned. The centers measured ≈80 ft, but the average pillar width was only 31 ft, resulting in an as-mined dimension ≈10% less than planned. In addition, the mining height in the benched area measured 58 ft. It is estimated that the as-mined dimensions, reduced the *w/h* from 0.66 to 0.54 (Esterhuizen et al. 2019).

The standard deviation of the pillar widths around the perimeter of the fall was 4.5 ft (Esterhuizen et al. 2019). Therefore, a similar pillar dimension variability likely existed in the pillar collapse area. Using the S-Pillar software, the FOS of the pillar collapse was slightly above 1.0 (Esterhuizen and Murphy 2010). The size of the benched area was approximately seven acres, some of which had been backfilled with fine crusher waste (Esterhuizen et al. 2019). As shown in Figure 3, the mine operator benched most of the pillar collapse area, apart from the unbenched travelway bisecting the pillar collapse area.

A prominent joint set, 500 ft wide in plan view, exists through the eastern half of the pillar collapse. The joint spacing was from 10 to 16 ft and dipped from 60 to 80˚. A low angle thrust fault along the southeast edge of the pillar collapse zone intersected the joint set. NIOSH conducted simulations after the pillar collapse and found that the large discontinuities coupled with the *w/h* = 0.54, resulted in a pillar strength lower than what could be predicted by established hard-rock pillar strength equations (Esterhuizen et al. 2019).



Adapted from Esterhuizen et al. 2019

Figure 3. Pillar collapse periphery at Mine A

Mine B – October 2020, Pennsylvania

On October 6th, 2020, approximately 25 pillars collapsed at a southwestern Pennsylvania limestone mine. This pillar collapse registered as a 2.9 magnitude event on the U.S. Geological Survey's seismic network. See Figure 4a for an image of the resulting subsidence and Figure 4b for an image of the pillar collapse perimeter.

(a) (b)

Figure 4. (a) Subsidence from collapsed workings and (b) an underground perspective of the rubblized periphery

The pillar collapse occurred in a benched region of the underground room-and-pillar works, with a depth of overburden of ≈160 ft (Figure 5). Development mining occurred five to six years prior to the pillar collapse, at a mining height of 25 to 30 ft, or 50% of the total height of the Loyalhanna Limestone Bed in the area of the collapse. Bench mining of the lower portion of the Loyalhanna was ongoing and conducted just four days prior to the pillar collapse. It was not evident if bench mining began recently or had been on-going since development. The full bench height ranged from 45.9 to 48.0 ft. Mudstones, shales, and siltstones overlay the mining horizon and operations left 8 ft of limestone in the roof to provide a stable back; however reliable data via drilling logs were not available to attest to the main and immediate roof thickness and composition in the vicinity of the collapse. It should be noted that while the immediate and main roof can be a contributing factor to pillar instability, the focus of these case studies was primarily on the generalized pillar geometry.

A contributing factor to the pillar collapse was the as-mined pillar widths being smaller than the planned pillar widths of 40 ft, which created unacceptable w/h values. Field measurements (n = 32) around the border of the pillar collapse indicated that ≈90% of the measured pillars were less than 40 ft and ≈13% were less than 30 ft. Along the periphery of the pillar collapse area, the average width was ≈35 ft with some as low as 25 ft, resulting in w/h of 0.53 (25.3 ft/48.0 ft). The mine plan showed the smallest width of a pillar inside the pillar collapse area as 20.6 ft, resulting in an even lower (estimated) w/h = 0.43. At the boundary of the pillar collapse area, where the pillar run ceased, and using a conservative pillar height of 45.9 ft, ≈44% of periphery pillars were below a w/h of 0.76.

The description of the notably complex structural geology of the Loyalhanna bed was consistent with previous ground-control work (Iannacchione and Coyle 2002). Specifically, nearly 375 measurements from mines within the Loyalhanna indicate two distinct joint sets. The first joint set exhibits mostly vertical jointing in the direction of N47˚W, and the second joint set is 90˚ offset at N48˚E at varying dips. The former set strikes across, and the latter set is nearly parallel to the Chestnut Ridge. Observed after the pillar collapse, were four joint sets (one longitudinal, one transverse, and two conjugates). The longitudinal joint set had strikes at N35˚E to N45˚E with variable spacing ranging from 10 to 20 ft and local joint clusters (i.e., three to six) at spacings from 5 to 10 ft. The transverse joint set had strikes measured at 7 to 16˚ offset from N47˚W, at N54˚W to N63˚W. These joints were non-persistent with dips to the southwest. Two conjugate sets were steeply dipping and displayed strikes at the upper and lower bounds of the northwest quadrant.

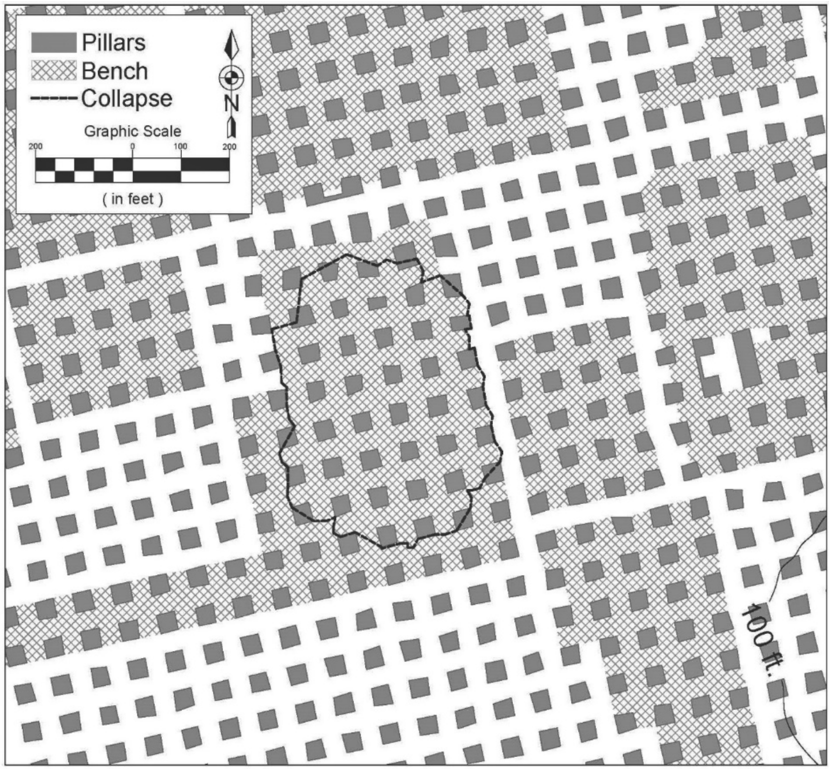


Figure 5. Pillar collapse periphery at Mine B

Mine C – November 2020 and July 2021, Pennsylvania

During the pre-dawn hours in November 2020, a surface miner returned to his worksite on a spoil pile where he had parked a brand-new excavator, with only 10 machine-hours on it, at the conclusion of his last shift. Surprised by not seeing the excavator, the miner stopped and exited his truck. Instead of finding the excavator, he realized that he was standing near the edge of the surface depression shown in Figure 6, and narrowly avoided driving into the sinkhole. The excavator is engulfed in the sinkhole and has not been found.

The sinkhole overlays room-and-pillar workings in the Valentine Limestone, which are part of an active mine owned and operated by a different company than the surface operation. The underground workings experienced a pillar collapse during the previous night. What occurred that morning would be the first of many sinkholes that would appear in the spoil pile area and adjacent properties. The cause of these sinkholes was the collapse of approximately 12 pillars, comprising six acres. In July 2021, a second pillar collapse occurred in the same panel, resulting in more subsidence and an airblast that caused damage to mine-infrastructure, including communication beacons, ventilation brattices, escapeway signage, haulage mirrors, and barricades.

The area of the second collapse involved approximately 20 pillars, covering nine acres. The surface subsidence, which was adjacent to an abandoned and an inhabited residence, manifested within 48 hours of the pillar collapse. This subsidence feature was approximately 800 ft south of the November collapse, 5 to 25 ft deep and comprising ≈3.5 acres of trees and a pond.

Figure 6. A 260 ft diameter by 100 ft deep sinkhole associated with the pillar collapse at Mine C

The July 2021 pillar collapse registered as two distinct seismic events on the regional Pennsylvania State Seismic Network of 1.4 magnitude at 3:45 AM and 2.6 magnitude at 4:00 AM local time. Nearly half of the 36 acres of benched area collapsed during these two events (Figure 7) and were the first failure of its kind since the mine began operations around 1950.

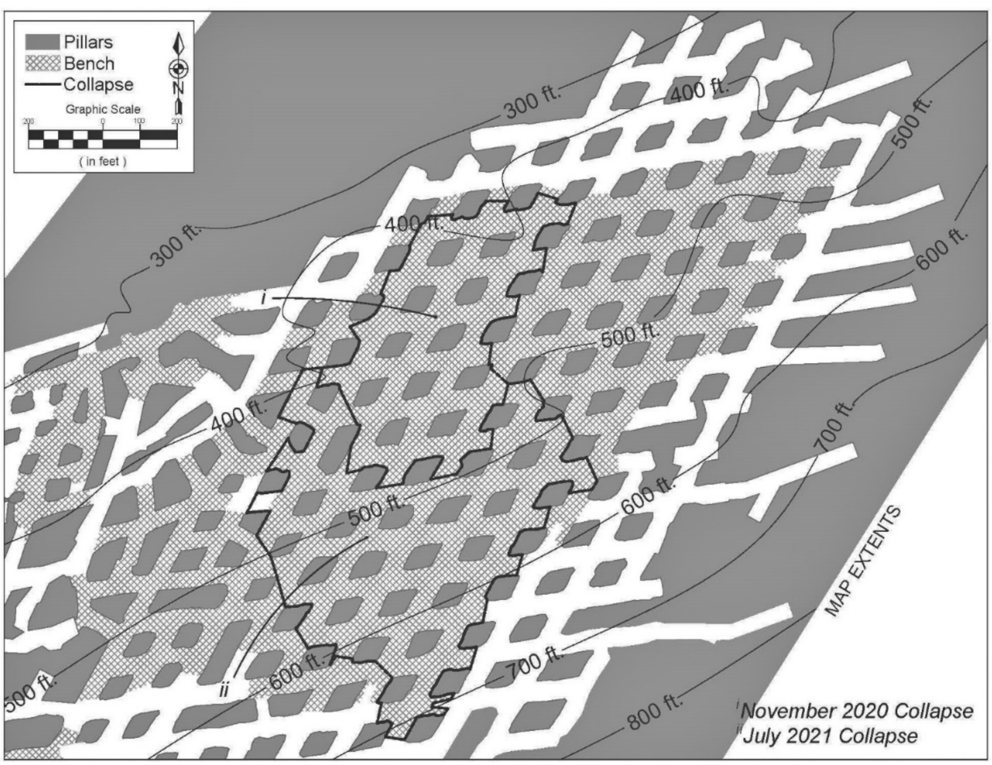


Figure 7. Pillar collapse regions at Mine C

The operator initially developed the panel that collapsed between 1998 and 2001, at a height of ≈30 ft. Benching occurred from 2002 to 2006, which increased the total mining height to 72 ft. The pillars were diamond-shaped, with north-south oriented headings developed 53° from the east-west headings. The seam dips from 10 to 15° to the southeast and center-to-center spacing between headings was 115 ft. The planned pillar widths were 65 ft. According to the mine operator, blasting during benching and spalling of the pillars over time may have reduced the pillar width to 55 ft. The depth of cover ranged from 350 to 650 ft.

The *w/h* of the pillars was ≈0.76 and analysis showed a FOS of ≈1.4 for the collapsed panel; both values were less than those that S-Pillar suggests (Esterhuizen and Murphy 2010). The *w/h* was calculated using the minimum width of the pillar. Moreover, there are several unaccounted factors in the software's calculations, particularly those associated with the dip of the seam, impact of adjacent face development, adjacent surface mine, overlying spoil pile, complex geology, and the angled headings and crosscuts. Most notable is that the seam dips from 10 to 15° and the S-Pillar database only includes flat-lying formations. A steeply dipping seam, such as this one, would further reduce stability of the pillars; therefore, the actual FOS is likely less than the S-Pillar calculated value of 1.4.

The mine operator had been developing the faces immediately east of the pillar collapse area for a few weeks prior to the pillar collapse. Miners had been traveling along the perimeter of the pillar collapse area during that time. The development work in the eastern faces likely influenced the pillar collapse as the overburden load would re-distribute and likely increase the stress on the benched pillars in the pillar collapse area.

An active surface mine was also extracting stone adjacent to the panel from the same formation. This surface mine had been regularly blasting immediately adjacent to the pillar collapse area for the 13 months preceding the pillar collapse. A seismograph in the northwest corner of the panel detected ground vibrations from surface and underground blasting, however, whether pillar stability was affected, or unaffected, by blasting cannot be made with a high level of confidence at this time. Nonetheless, the awareness of these adjacent activities is important.

Finally, the primary spoil disposal area for the adjacent surface mine was over the northern half of the panel. Satellite imagery shows initial construction of the spoil pile in the early 1990s. Over the past 30 years, the spoil height appears to have increased by 200 ft above the initial ground elevation, creating an increasing surcharge load on the pillars which may have contributed to their failure.

Mine D – August 2021, Tennessee

In August 2021, a foreman started his examination shortly before 5 AM. While traveling on a roadway adjacent to benched legacy workings, he heard falling rock. Over the course of the next hour, the foreman and other miners heard what they described as "large," "loud," and "continuous" falls of rock coming from the area. During this same time, one of the haul truck operators discovered recently spalled material from a pillar rib. The material was blocking the main haul road out of the production area adjacent to these benched legacy workings. This spalled material was in the same location where material had just been scaled from the rib and cleaned up the prior day. The foreman then evacuated all personnel from the mine.

The miners tagged out and gathered at the mine office, near the portals of the mine. Suddenly a pillar collapse occurred. The miners reported feeling a pressure pulse or wave, heard rumbling from the portals, then watched an airblast with a velocity between 120 and 180 mph exit the portals. The airblast damaged nearby infrastructure and buildings and resulted in a sinkhole that encompassed an area of approximately nine acres as shown in Figure 8. Fortunately, no injuries occurred. The pillar collapse registered as a 3.1 magnitude seismic event. The pillar spalling and the resulting rock that miners noticed on the roadway on the day before the pillar collapse was an indication of the changing stability conditions. Miners cleaned up the material and scaled the pillar but observed fresh fallen material on the morning of the pillar collapse. During the months following the pillar collapse, miners did not go underground until the mine operator remotely examined the mine with autonomous mapping drones and Wi-Fi controlled ground robots and determined that the mine was stable.

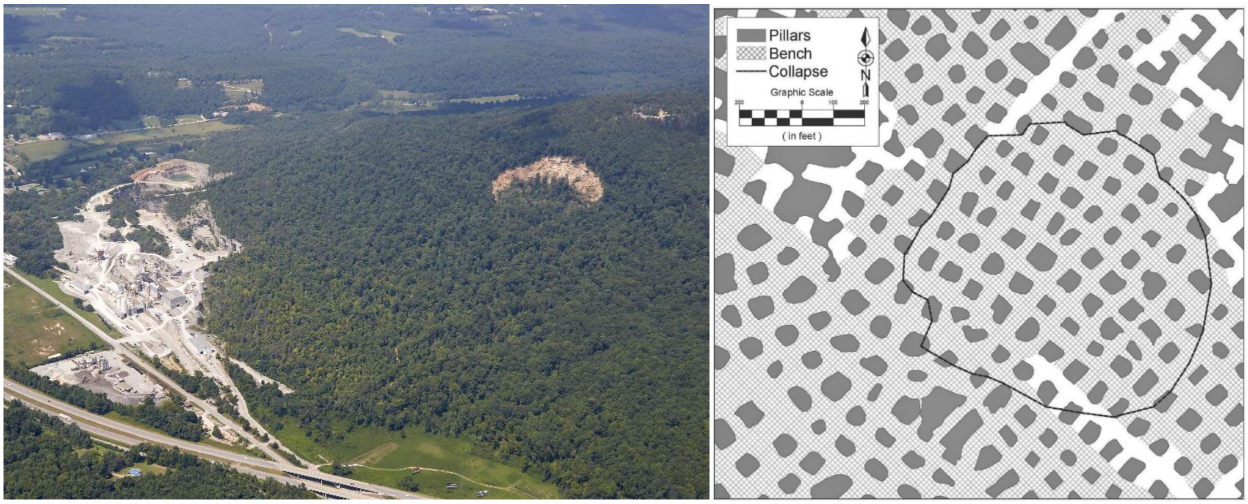


Figure 8. Sinkhole associated with the pillar collapse at Mine D and the associated underground plan view

The exploration program indicated that approximately 40 pillars, developed 70 years prior, collapsed across an area of 14 acres. Extracted over the next 35 years were two floor benches making the total mining height between 80 and 90 ft. The depth of cover was approximately 400 ft. The pillar widths were 36 ft minimum and averaged 53 ft. These widths suggest that the minimum *w/h* ranged from 0.40 to 0.45 for the pillar collapse area.

The collapsed pillars had been the subject of a pillar stability study in 2005 which included field measurements and photographs as shown in Figure 9. As were the circumstances in two of the other cases, nearby development mining had recently taken place. Since 2012, development headings had extracted a large barrier of intact limestone directly north of the area that collapsed. The presence of through-going joints in the pillars and karst features may have also been factors in the pillar collapse.

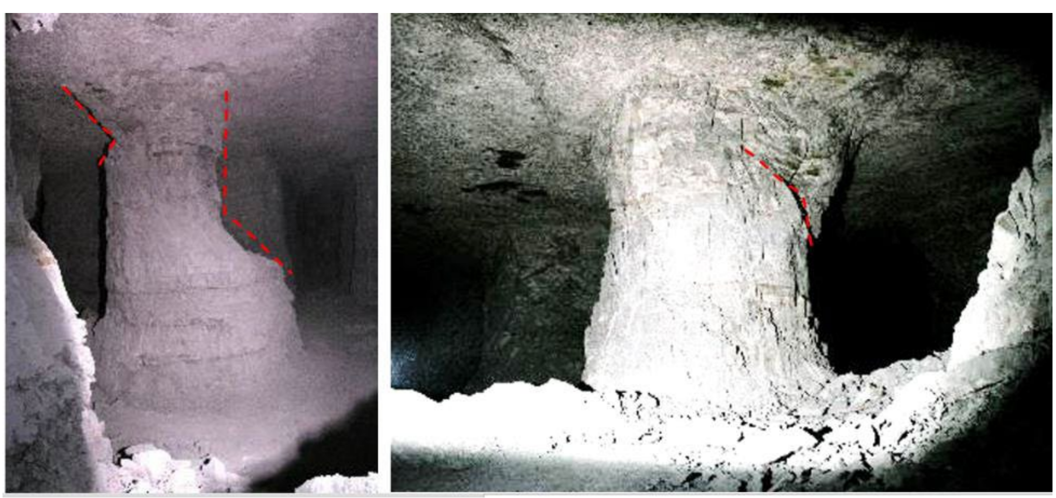


Figure 9. Pillars involved in the massive pillar collapse of Mine D (Photo credit: Dr. G.S. Esterhuizen)

DISCUSSION

Many active underground mines contain legacy workings. Evidenced by these case studies, legacy workings, particularly benched areas where the *w/h* does not satisfy modern design recommendations, may be prone to pillar collapse. These cases demonstrate the need for a risk management approach to assess the likelihood and consequences of pillar collapses in similar workings.

A proposed qualitative approach for assessing these legacy areas consists of the following steps. First, a mine operator identifies an area of standing pillars and evaluates the likelihood of a collapse of the pillars, based on the factors such as those in the Massive Pillar Collapse Likelihood Matrix (Table 1). This matrix helps define the geotechnical and mining geometric data necessary to conduct the pillar collapse assessment. The assigned factors are high, moderate, or low in rating. A high rating suggests an increased potential for a pillar collapse and a low rating suggests a decreased potential. All factors should be considered, even though there is no standard method for combining the individual factor ratings at present. Rather, a mine operator can assess the overall likelihood of a pillar collapse based on an evaluation of all the factors in the matrix.

Table 1. Massive pillar collapse likelihood matrix

	Low	**Moderate**	**High**
Pillar stability	Meets all applicable design criteria		Does not meet applicable design criteria
w/h (pillar system average)	$w/h>1.0$	$0.8<w/h<1.0$	$w/h<0.8$
Pillar dimension variability	All pillars approximately equal size	A few pillars smaller than average	Many pillars smaller than the average
Spanning potential of panel/benched area	Strong overburden/deep cover/narrow pillar array	Moderate strength overburden/moderate cover/moderate pillar array width	Weak overburden/shallow cover/wide pillar array
Size of benched area	Small	Moderate	Large
Major geologic features	None	If a fault, karst, or other major geologic feature is present, assess its potential contribution to the collapse likelihood	
Soft floor	None	Possible, but minimal evidence of pillar distress	Thick weak floor causing pillar dilation
Weak bands in the pillars	None	Possible, but minimal evidence of pillar distress	Thick, weak band causing pillar dilation

The first two factors, pillar stability and *w/h*, are the most critical. Assessment of pillar stability occurs with software such as S-Pillar or other widely applied and successful pillar design methods. The analysis must consider the depth of cover, extraction ratio, actual pillar dimensions, limestone strength, and the presence of joints or other geologic features. Since mine maps can be inaccurate, especially in legacy areas, verifying the actual pillar dimensions is important. The results can then be compared to the design method's criteria. Some design methods have limitations or restrictions for their use, such as ranges of mining geometries, rock strengths, or other geologic characteristics. The *w/h* is the second component of the pillar analysis. A pillar array with an average *w/h* less than 0.8 is a concern because the strength of slender limestone pillars can be difficult to accurately quantify. The variability of pillar dimensions is also important because if some pillars within the array are significantly smaller than the others then these smaller pillars can fail first, transfer stress to neighboring pillars, and subsequently trigger a pillar collapse.

The tributary area theory assumes that a pillar carries its full share of the overburden weight. Only a few pillars in the center of the array may carry the full tributary area load, while the pillars near the edges of the panel may be shielded due to arching from barrier to barrier. When the pillar array is narrow, the cover is deep, and/or the overburden is strong, a pressure arch can transfer load so that pillars carry less than the full tributary area load; this can decrease the likelihood of a pillar collapse. Conversely, when the overburden is weak, the cover is shallow, and/or the panel is wide, a pressure arch may not transfer load and the pillars may carry the full tributary area load; this can increase the likelihood of a pillar collapse. Therefore, pressure arching directly affects pillar collapse potential.

Research has also identified several geologic factors related to the likelihood of a collapse. A major geologic feature, such as a fault or karst, can weaken the overburden and/or decrease the strength of pillars within an array. A soft floor can also reduce pillar strength by foundation/shear failure (heave or punch) resulting in pillar slabbing and roof deterioration. Clay layers or other weak banding can affect pillar stability. Rib dilation and slabbing increases the likelihood of collapse by reducing a pillar's strength and its load bearing area (Esterhuizen et al. 2011). The operator should note the presence of karsts within the mining units and look for karstic subsidence features and water features on the surface overlying these areas.

The next step of the risk management process is to evaluate the consequences of the potential pillar collapse. The Massive Pillar Collapse Consequence Matrix (Table 2) can serve as a guide to conduct the evaluation, considering the potential hazards that would be present in different locations in the mine, and the exposure of miners to those hazards. For areas where the combination of likelihood and consequence is great enough, the mine operator can take measures to mitigate the risk (Mark 2021).

Table 2. Sample massive pillar collapse consequence matrix

Location of Miners	Conditions/Hazards	Consequence	Miners Exposed, #	Exposure Freq.
Working within pillar collapse area, engaged in active benching operations	Massive rock fall, no warning	Death		
Working or traveling in travelways or haul roads directly adjacent to pillar collapse area	High air velocities, flying debris, small rock falls	Death or severe injury		
Working or traveling directly above a pillar collapse area	Sudden development of a surface sinkhole	Death or severe injury		
Working or traveling in high velocity air pathways leading from pillar collapse area to portals	Diminishing air velocities depending on number of pathways and distance from pillar collapse	Injury		
Other locations in the mine	Damage to ventilation controls or egress routes	Indirect hazards		

If a pillar region has an elevated likelihood of pillar collapse, control techniques could reduce the consequences of a potential pillar collapse. For example, a mine operator can reduce exposure to a pillar collapse and airblast by relocating travelways and other mine infrastructure to areas of lower potential. This method might be particularly appropriate for infrastructure or travelways located directly adjacent to a potential collapse area.

Another control is to establish airblast-attenuation barriers, such as bulkheads, or rock barriers, as a precaution to protect miners and infrastructure. Properly designed barriers are those where the bulkhead material cannot become airborne. Backfilling a pillar array, with fines or blasted material, could reduce the intensity of an airblast, because it reduces the void volume. Backfilling may provide some confinement to the pillars, however, one of the areas described within this paper was partially backfilled prior to the pillar collapse.

A monitoring program could also serve as a valuable tool to complement the pillar collapse management program. Trained mining crews can observe warning signs, such as rock noise emanating from pillars, or new rib spalling via pillar condition surveys. Monitoring programs could include real-time measurement such as micro-seismic monitoring which could potentially provide early warning of pillar failure. The monitoring program would include a record keeping system accompanied with management processes developed to ensure that warning signs receive appropriate and expeditious responses. Technologies, such as LiDAR-equipped drones, could aid in the program and provide mine operators the capability to gather pillar dimensions for the pillar collapse assessment with high resolution and accuracy. Periodic surface inspections can identify subsidence, karst features, and changes in water features that may serve as precursor indicators of pillar collapse and can be easily implemented with current drone capabilities.

SUMMARY

There is clearly a need to evaluate the stability of active *and* legacy workings. Three of the four mines in the case studies had travelways adjacent to legacy workings that collapsed. Two of the mines had active faces adjacent to the legacy workings that collapsed. Some commonalities emerged from the five pillar collapse cases (Table 3). The depths were relatively shallow, ranging from 160 ft to 600 ft. Each pillar collapse created surface subsidence and registered on regional seismic networks. The pillar collapse areas included 12 to 40 failed pillars and encompassed 5 to 15 acres. The collapsed pillars were in benched areas where the mine operator extracted the floor after initial development, which created slender pillars with total heights ranging from 50 to 80 ft and *w/h* ranging from 0.45 to 0.76. These ratios are below the 0.8 minimum value recommended by NIOSH, and demonstrate the need to maintain dimensions that meet, or exceed, recommended design values (i.e., FOS) and criteria.

Table 3. Characteristics of the five pillar collapse areas

	Mine A	Mine B	Mine C		Mine D
Pillar collapse date	Apr. 2015	Oct. 2020	Nov. 2020	Jul. 2021	Aug. 2021
Overburden, ft.	200	160	500	600	400
Bench height, ft.	58	50	72	72	80
w/h (min.)	0.54	0.63	0.76	0.76	0.45
Pillars	35	25	12	20	40
Pillar collapse area, ac.	7	5	6	9	14

The five recent pillar collapses represent an alarming number, considering there are only about 100 limestone mines operating in the United States. For planning purposes, existing underground mines may appear attractive to access reserves without requiring new permitting or logistical challenges. However, these mines may contain areas of legacy pillars developed without modern pillar stability evaluation techniques. Although assessment of legacy areas is not routine, legacy areas can still be a significant hazard to miners. Mine operators should carefully evaluate active mining areas, particularly when they are benching. Fortunately, no fatalities occurred during these recent pillar collapse events; however, three miners did sustain serious injuries and many miners narrowly avoided fatal or serious injuries.

REFERENCES

Esterhuizen, G.S., and Murphy, M.M. 2010. S–Pillar (Version 1.02). U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Office of Mine Safety and Health Research. https://www.cdc.gov/niosh/mining/works/coversheet1817.html.

Esterhuizen, G., Dolinar, D.R., and Ellenberger, J.L. 2011. Pillar strength in underground stone mines in the United States. *Int. J. Rock Mech. Min. Sci.* 48(1):42–50.

Esterhuizen, G.S., Tyrna, P.L. and Murphy, M.M. 2019. A case study of the collapse of slender pillars affected by through-going discontinuities at a limestone mine in Pennsylvania. *Rock Mech. Rock Eng.* 52:4941–4952. doi:10.1007/s00603-019-01959-6.

Iannacchione, A.T., and Coyle, P. 2002. An examination of the Loyalhanna limestone's structural features and their impact on mining and ground control practices. In *Proceedings of the 21st International Conference on Ground Control in Mining*, Morgantown, WV, August 6–8. Morgantown, WV: West Virginia University.

Mark, C., Chase, F.E., and Zipf, R.K. 1997. *Preventing Massive Pillar Collapses in Coal Mines*. DHHS (NIOSH) Publication No. 97-122. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Mark, C. *Assessing pillar collapse and airblast hazards in underground stone mines.* Presented at the Mt. Pleasant District Stone Mine Outreach Seminar, Virtual Meeting, November 9, 2021.

Mark, C, Rumbaugh, G. 2022. *International Experience with Airblasts and its Relevance to Underground Stone Mines*. Proc. 41st Intl. Conf. on Ground Control in Mining, in press.

Nelson, C. *Overview of recent pillar collapse events*. Presented at the Underground Stone Safety Seminar, Marriott Hotel, Louisville, KY, December 7–8, 2021.