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MONITORING OF MULTIPLE-LEVEL STRESS INTERACTION AT TWO UNDERGROUND LIMESTONE MINES

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) has previously established pillar design guidelines for shallow, flat-lying mines and single-level operations. Little guidance exists for ground control design in multiple-level stone mines and understanding the interactions between levels would allow engineers to better select interburden thicknesses and the necessary amount of pillar columnization. To investigate these loading conditions in multiple-level environments, NIOSH has partnered with two separately operated multiple-level mines to study the stress interaction between the levels as undermining occurs. The first mine is located in Tennessee with up to a 243-m overburden and 7-m interburden thickness between levels. The second mine is located in Kentucky with a 304-m overburden and 26-m interburden thickness between levels. The monitoring program at these sites includes stressmeters and LiDAR for tracking stress redistributions and rock displacement in response to undermining. Monitoring is ongoing, but numerical modeling results show the expected interaction between levels.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) is investigating the stability of pillars in challenging underground stone mines. At the time of this publication, there are approximately 110 underground stone mines in the United States, many of which are operating in multiple-level environments. Many existing surface quarries are also transitioning underground due to reaching their economic stripping ratio, approaching reserve boundaries, and the dust, noise, and blasting concerns to surrounding urban and suburban areas (1). The decision to take an existing underground mine into multiple levels may be due to property boundary issues but can also be grade-dependent.

The efforts outlined in this paper intend to build on the work of Esterhuizen et. al. and the investigations that led to the development of the pillar strength equations found in the S-Pillar software (2)(3). The applicability of this research is intended for shallow, flat-lying, single-level underground stone mines, because the empirical database represents conditions from a majority of underground limestone mines that were operating at the time. This does not necessarily preclude its use in other situations, but numerical modeling is frequently employed alongside it to better understand the complex loading environment in multiple-level mining (1)(4). Questions regarding critical interburden thickness and pillar columnization need to be answered to confidently design stable pillars in these complex conditions.

Additional levels, above or below existing workings, will change the location and magnitude of stress concentrations depending on how the pillars are positioned relative to each other. Interaction between levels in underground stone mines is undesirable, because it often redirects stresses away from the stable core of the pillar, but what constitutes a significant interaction is difficult to define. Any excavation above or below existing workings is going to have an impact on ground stability, but the magnitude of that impact is likely to be largely dependent on the thickness and mechanical properties of the interburden and the amount of pillar columnization. Attempting to vertically align pillars across levels is commonly referred to as columnizing, superimposing, or stacking, and the effect this can have on vertical stress is illustrated in Figure 1. As it passes through a pillar, if pillars are columnized, the stress remains largely unperturbed, but can rotate through the interburden if the pillars are offset. Rotation of the stresses through the interburden can cause stress concentrations, especially at the top pillar-opening corner, that could induce failure in an otherwise competent beam.

Interburden stability and stress interaction between levels in multiple-seam coal mining has been heavily researched over the past several decades (5)(6)(7). Much of this research and discussion is focused on the role that gob-solid boundaries, subsidence, and pillar columnization play, as well as the mechanical influence of an interburden consisting of coal measure rocks. In metal mining, mine geometries, mining methods, and rock types tend to vary too significantly to provide a consensus means of characterizing interburden stability and stress transfers. However, some metal mines do approximate multiple-level room-and-pillar layouts, such as the Elliot Lake mines described by Hedley (8), which formed the basis of the Hedley and Grant size effect formula for pillar strength.

The applicability of some of these ideas that have been researched in the past, specifically from the body of multi-seam coal mining research, is beyond the scope of this paper. However, several of the ideas these authors explored should be highlighted, because the same rock mechanics concerns apply. What is the critical stable interburden thickness? In the case of thin interburden, can the pillar height be considered separately for each level, and if not, what stabilizing impact does the interburden provide? How does stress transfer through pillars that are poorly columnized? These questions need to be considered for underground stone mining and are the reasons this study is being performed.

MONITORING METHODS

Site A Monitoring Program

The first case study, Site A, is a multiple-level limestone mine located in Tennessee, mining the Monteagle Limestone. The mine varies from 10- to 245-m deep. The Monteagle Limestone is a 45-90-m thick Mississippian age member of the Pennington Formation. The Monteagle Limestone is commonly oolitic fine to coarse grained and white to light gray in color (9). The upper level of the mine is a massive, light-colored oolitic limestone that contains very few joints that are intermittently spaced in two directions. The main joint set is N5E degrees, and the secondary joint set is N56W. Stylolites are common in the upper seam and are measured on average of 0.6-m apart. Jointing is very prominent on the lower level of the mine, causing rib stability issues. The lower level limestone is highly crystalized and darker gray in color when compared to the upper level limestone.

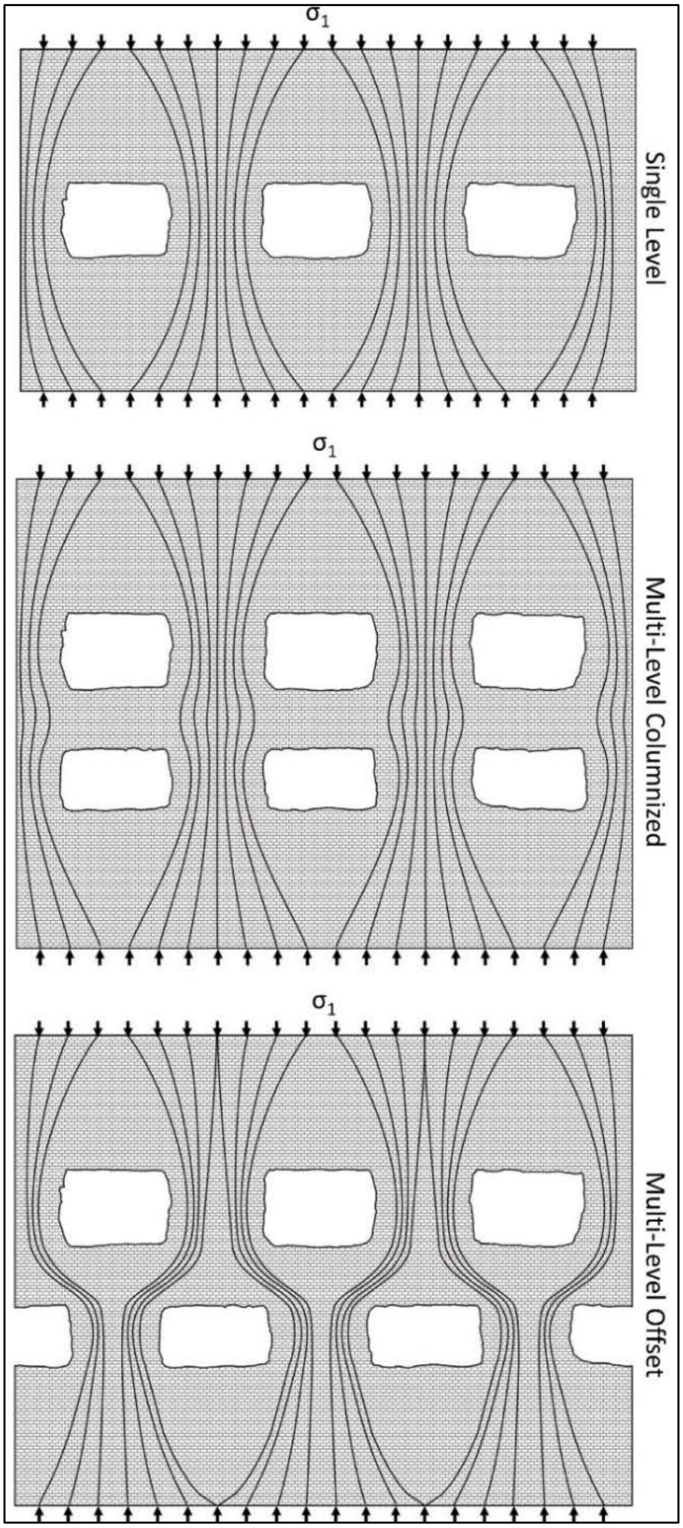

Figure 1. Conceptual rendering of stress transfer through multiple levels.

The upper and lower level pillars are both 13.7 by 13.7 m and the openings are 15.2-m wide on both levels. The mining height is 9.1 m on both levels, and approximately 20% of the mine is pattern bolted. This mine has a very thin interburden between 6 and 8 m, especially when compared to the excavation width. The pillars are also columnized. Planned dimensions cannot be expected to perfectly agree with mined dimensions, and as a result pillar offsets of 1 to 2 m from the upper level to the lower level are common. There has been one instance, in this mine, of significant interburden instability in an area with poorly columnized pillars. There are no signs of an elevated horizontal stress, so it is also unlikely that undermining will have a large impact on the horizontal stress field. Testing these expectations with field instrumentation and numerical modeling is the goal of the Site A monitoring program. An area surrounding a pillar that would soon be undermined, called the “study area” and “study pillar” was chosen on the upper level to instrument with stressmeters and accelerometers. The instrumented area is shown in Figure 2.

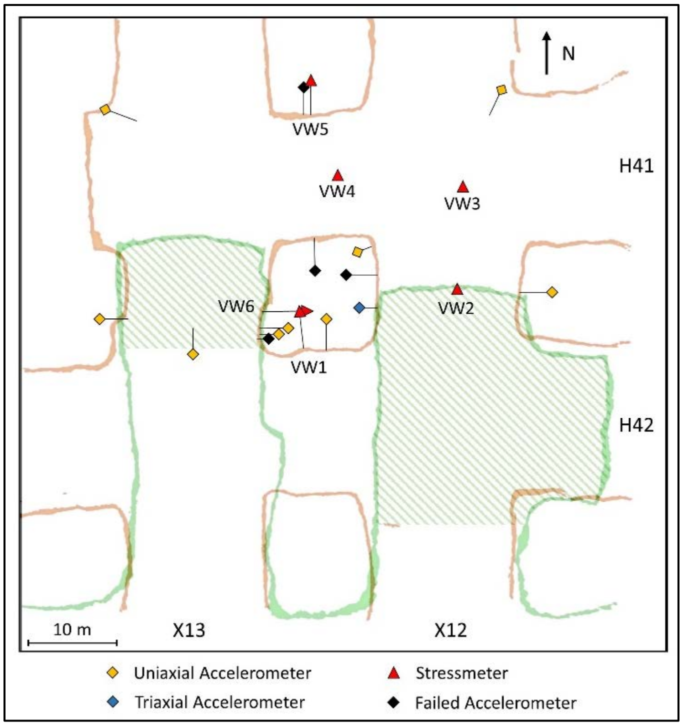

Figure 2. The study area is shown with upper level workings in orange and lower level workings in green. The hatched green area represents development that has occurred on the lower level throughout the monitoring period. All the accelerometers are dipping between 25 and 40 degrees.

Site A consists of a three-tiered program to monitor seismic response, changes in stress, and displacement of the rib, roof, and floor. The seismic monitoring currently includes nine uniaxial accelerometers and a single triaxial accelerometer. The original installation included only uniaxial accelerometers, but following the failure of three sensors, it was decided to replace them with a single triaxial sensor to improve seismic event location accuracy. The seismic sensors are grouted at various angles, orientations, and depths into the rock surrounding a pillar and the interburden underlying it. Even though the rock is largely homogenous, a three-dimensional velocity model has been developed for the study area, due to the large void spaces in close proximity to the sensors and microseismic sources.

The stress monitoring consists of six vibrating wire biaxial stressmeters. Five of the stressmeters are installed from the upper level, one subhorizontal in the study pillar (VW1), another subhorizontal in the adjacent pillar north of it (VW5), and three subvertical in the interburden surrounding the study pillar (VW2, VW3, and VW4). The sixth stressmeter is installed subhorizontally in the rock that will become the pillar underlying the study pillar (VW6). The intent was to only capture vertical loading in the pillar and horizontal loading in the interburden, but due to equipment limitations, perfectly vertical and horizontal holes could not be drilled. As a result, it is expected that the subhorizontal stressmeters may slightly underestimate vertical loading and the subvertical stressmeters may slightly underestimate horizontal stress changes.

The displacement monitoring is being performed using an I-Site 8200 terrestrial laser scanner and scanning every 70 to 80 days. On the upper level, scans were collected from the middle of the opening on each side of the pillar and each intersection. On the lower level, scans were collected in as many places as required to capture the new excavation geometry, but at the same approximate scanner spacing as the upper level. The scans were initially registered to mine survey points, but global registration to the previous set is used for all change detection. Past experience with similar monitoring (10) showed that displacements as small as several millimeters can be detected.

For Site A, this paper will review stress, seismic, and displacement data results collected from October 2018 through August 2019. Monitoring will continue until undermining of the instrumented area has been completed, which is expected to require an additional 1-–2 years.

Site B Monitoring Program

The second case study, Site B, is a multiple-level limestone mine located in Kentucky. The mine operates on two levels in separate formations. The Tyrone Limestone is mined in the upper level of the mine, which is about 285-m deep, and the Camp Nelson Limestone is mined in the lower level. Both the Tyrone and the Camp Nelson formations are members of the High Bridge Group, which was deposited during the middle Ordovician Period approximately 460–455 million years ago. The seam thicknesses in these formations can vary from 17 to 47 m and contain a variety of limestone types (11).

Pillars on the top level are planned 18.3 by 18.3 m, and pillars on the bottom level are 27.4 by 27.4 m. Openings are 12.2 m wide on the top level and 13.1-m wide on the bottom level. Mining height is nearly 11 m on the top level, and an ultimate planned benched height of 18.3 m is expected on the bottom level. The mine currently pattern bolts active areas at 1.5 x 1.5 m spacing, but the monitored area contains older workings and was not bolted. The top-level pillars contain six limestone beds and one chert layer. The upper two limestone members were massive and approximately 8.7-m thick collectively. The third member from the roof was the chert member, which averaged 0.15-m thick and tended to be very brittle. From the chert layer to the floor, the lithology became thinner and subject to a higher density of jointing. The jointing in the lower five beds was measured in orientations of N52E with a near vertical dip and N34W and a dip of 80 SW at a 0.15-m to 0.3-m spacing with an overall thickness of 2.0 m.

An interburden thickness of 26 m was initially selected at this mine to provide a large enough barrier between the levels to ensure there would be no concern about interaction. Because of this, the pillars are not columnized and the pillars are different sizes. The goal of the Site B study is to determine whether any significant interactions do exist between the levels, despite the large interburden thickness.

Site B consists of a stress and displacement monitoring program. A monitoring area was selected that would be undermined within the next 1–2 years. The area selected should also show the extremes of potential stress changes. Due to the difference in pillar sizes between the levels, a repeating pattern of overlap exists that creates areas that could be expected to produce large stress changes if there was an interaction between the levels. This area is shown in Figure 3. Six vibrating wire biaxial stressmeters were installed such that two would capture an ultimately decreasing stress, two would capture an ultimately increasing stress, and two would lie somewhere in between.

FLAC3D models were conducted to examine the effect of multilevel mining at Site B, assuming two different interburden thicknesses. An elastic material model was assumed for the pillars, the roof, and the floor. The top level is composed of an 8x8 array of pillars, and the bottom level is composed of a 6x6 array of pillars, all approximately matching the planned mine dimensions. Roller boundary conditions were applied for the vertical sides and the bottom of the model. The first 60 m of the roof was modeled with a surcharge equivalent to the remaining depth of cover applied on the top surface of the model. The element size for the pillars was kept constant for all models to eliminate the effect of element size on stress distributions.

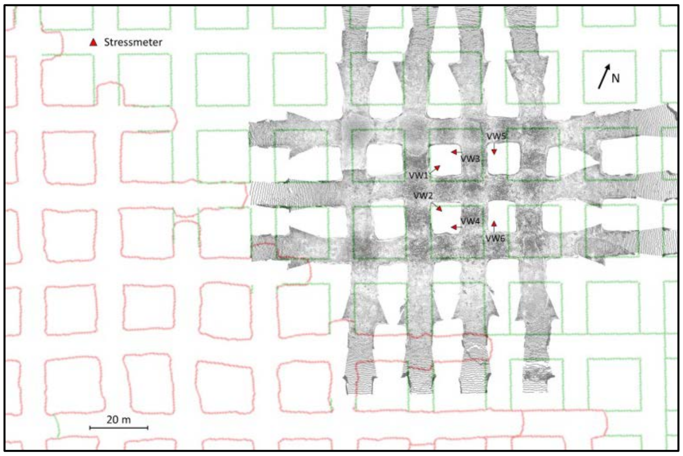

Figure 3. The study area is shown with the LiDAR scanned geometry of the upper level overlain on the lower level development (red) and lower level projections (green) near the time of installation.

The model was solved in three stages: (1) Geostatic, to initialize pre-mining stresses, (2) Top level development, and (3) Bottom level development. For elastic models, the only input parameters for the model are the rock mass Young's modulus and the Poisson's ratio. The assumed Poisson's ratio and Young's modulus are 0.25 and 50.8 GPa respectively, as previously measured at this mine. The rock mass modulus for the modeled pillars was estimated based on Hoek and Diederichs (12), shown in Equation 1.

$$E_{rm} = E_i \left[0.02 + \frac{1 - \frac{D}{2}}{1 + \exp\left[\frac{60 + 15D - GSI}{11}\right]} \right] \quad (1)$$

where E_{rm} is the rock mass modulus, E_i is the intact rock modulus, and D is the disturbance factor. The disturbance factor is assumed to be 0 because no significant blasting-induced damage was observed on the pillars.

LiDAR scanning is also being performed, similar to that described for Site A, but not as frequently because the area is larger and the effect from each blast is expected to be significantly less due to the larger interburden. Convergence of the opening is not expected to be significant enough to detect, but some spalling may result from shifting stress concentrations.

The instruments at Site B were installed in August 2019 and will continue to be monitored through the full undermining of the instrumented area. This is expected to take an additional 1–2 years, with the ultimate benched height being developed several years afterwards.

PRELIMINARY RESULTS AND DISCUSSION

Site A and B Stresses

For Site A, results of monitoring are shown in Figure 4 and Figure 5 for a period of October 2018 to August 2019. The stresses are zeroed to one month after installation to ensure the grout had cured. Refer to Figure 2 to see the extent of undermining during this time. The vertical stress is shown for the three stressmeters installed horizontally into pillars: VW1, VW5, and VW6, or "pillar stressmeters,". All the stressmeters show a general trend of increasing stress, but VW1 shows stress measurements are punctuated by steep drops following nearby blasting. Nearly every blast within 30 m shows a visible drop in stress immediately following the blast, except for the blast on February 19th, 2019, which is followed by a clear increase in stress. Since the end of May 17th, 2019, no development has occurred surrounding the study pillar, and no large drops in stress are observed. VW5 and VW6 do not show the same stress drops as seen in VW1, but VW6 was installed after most of this nearby blasting had already occurred, and VW5 was never within 30 m of the blasts, so this behavior may be yet to occur.

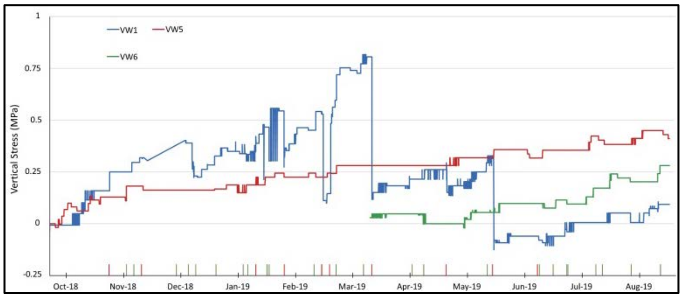

Figure 4. Vertical stress for the vibrating wire biaxial stressmeters installed subhorizontally into two pillars in the study area at Site A. Red tick marks along the date axis indicate blasts within 30 m and green tick marks represent blasts within 60 m.

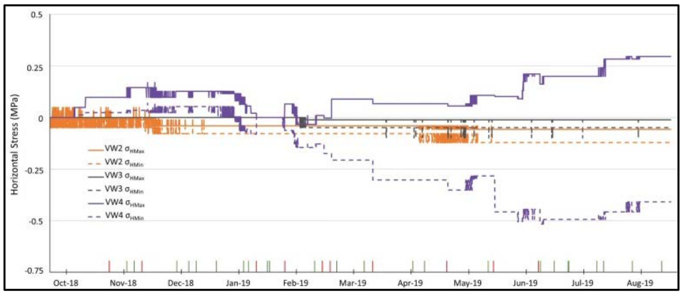

Figure 5. Horizontal stress for the vibrating wire biaxial stressmeters installed subvertically into the interburden surrounding the study pillar at Site A. Red tick marks along the date axis indicate blasts within 30 m and black tick marks represent blasts within 60 m.

The horizontal stress is shown for the three stressmeters installed vertically into the interburden: VW2, VW3, and VW4, or “interburden stressmeters,”. The horizontal stress is not shown for the pillar stressmeters because it is expected that any stress change should be vertical, and the assumed installation angle has been modified to minimize any horizontal stress changes. VW2 and VW3 have shown no significant change in horizontal stress. VW4 has shown a significant change in both the major and minor horizontal stress, becoming more pronounced as development approaches the sensor.

The stressmeters at Site A have been in place long enough to capture significant undermining of the instrumented area. The pillar stressmeters should show changes to vertical loading, while the interburden stressmeters should show changes to horizontal loading. There is no indication of an elevated horizontal stress at this mine, so changes to the horizontal loading condition would likely be due to interactions between the levels and a rotation of the vertical stress. In the case of the instrumentation at Site A, all six stressmeters should see minimal change if the pillars are perfectly columnized. There would be little reason for the vertical stress to rotate through the interburden, and there would be no reason to expect a significant increase in the vertical load on the top level, because the rock being removed from the bottom level should be providing very minimal support to resist the weight of the overburden. The absence of significant changes to horizontal loading of the interburden stressmeters is expected. The gradual increase in vertical load, punctuated by sharp changes following blasts, is also expected in the pillar stressmeters. Further undermining will need to occur before conclusions can be made about how successful the columnization is at predictably transferring stress.

For Site B, stressmeters have not been in place long enough to have obtained meaningful results, and they are not included in this paper; however, numerical models have been generated that show the expected stress change that will result from undermining. Figure 6 illustrates how the stress varies across the pillars on the top level depending on the layout of the underlying pillars and interburden thickness. Results are shown for both a 26-m interburden case that represents the actual conditions of the mine and a 13-m interburden case to highlight the effect the offset caused by a pattern of 18-m and 27-m pillars. According to the modeling, the stressmeters should see an ultimate change of <0.2 MPa in most places, and about 1 MPa at the greatest extremes, given the planned mine geometry. In the hypothetical thinner interburden case, 1–2 MPa changes are expected throughout when undermining occurs, with the extremes ranging from -1.5 MPa to over 4 MPa. Pillars on the top level that lie on top of openings on the bottom level show decreasing stress, while pillars that lie on top of pillars show higher stresses.

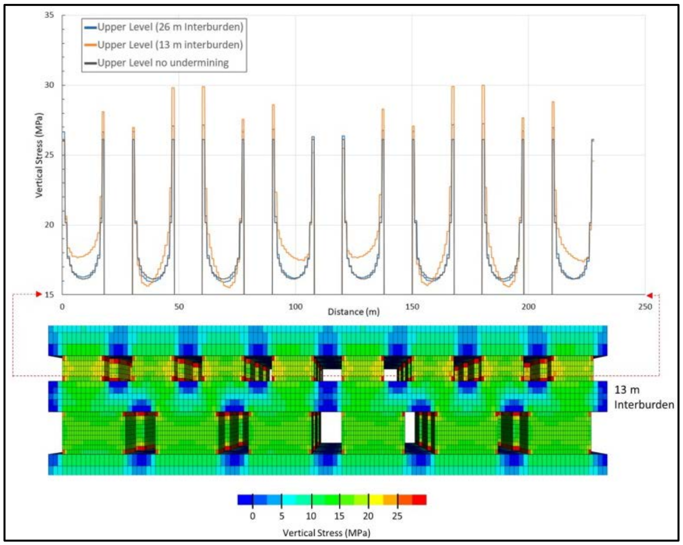

Figure 6. The vertical stress is shown as it passes through the base of the pillar on the top level for a case with 1) No undermining, 2) A 13 m interburden, and 3) A 26 m interburden. The FLAC3D numerical model shows an example of the model geometry for the 13 m interburden case.

When considering the factor of safety for hard-rock pillars, stress is typically assumed based on adjacent development and tributary area. These modeling results demonstrate that when you undermine existing works, at the mine scale, some pillars in a system may be loaded much more than other pillars at high excavation span to interburden width ratios. At the pillar scale, one side or corner of a pillar may become loaded more than the others, which could result in gradual reduction in pillar size and supporting capability if large amounts are able to spall away.

Site A and B Displacement Monitoring

At Site A, the LiDAR scans show displacements in the rock mass that occur in the months between visits to the mine by NIOSH researchers. Most of the displacements observed are spalling of the ribs, such as what is shown in Figure 7A. In this instance, the rib progressively spalls with time, ultimately reaching a depth into the pillar of 142 cm. Occasionally, there is a warning that spalling may occur, where displacement is observed prior to loose rock falling off the rib, as shown in Figure 7B. Five cm of displacement was observed before the piece of rock in this intersection fell; however, it is unknown how much more movement may have occurred between May and August when the failure was observed. The amount of spalling on the upper level is not alarming, however, it is localized, and appears to occur more frequently near areas that are undermined.

There are no widespread changes in the monitored area. The roof on the top level is not moving, and the roof on the bottom level only has very small localized areas where rock flaked off or was scaled away. The floor on both the top and bottom levels is showing no signs of movement. The ribs on the top level do show small amounts of spalling, as shown in Figure 8, seemingly correlated with development on the lower level, but there are no large spalling events nor is there any observed bulging or dilation of the pillars. The ribs on the lower level show large amounts of rib spalling near the active excavation. Whether these displacements are due to scaling or occur naturally cannot be distinguished, but the amount of material coming off the ribs near the active face is not atypical of underground stone mining.

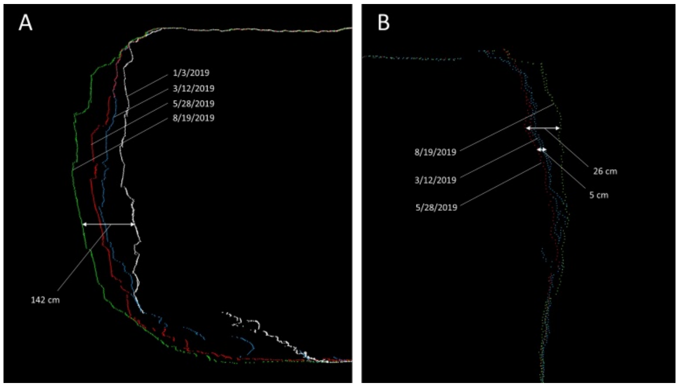

Figure 7. Rib displacement shown as it A) progressively spalls over a period of 7 months, or B) first displaces into the opening and later falls or is scaled down.

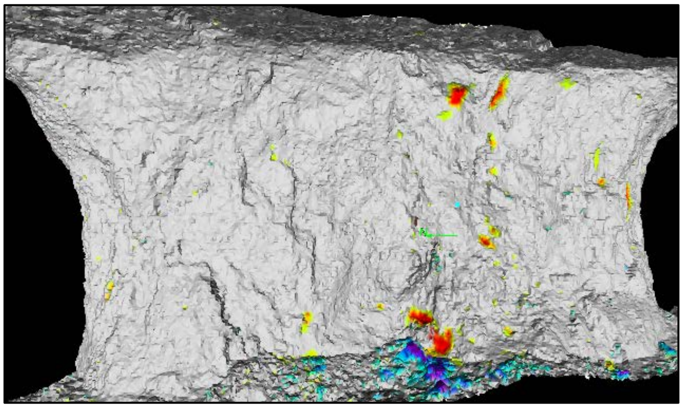

Figure 8. Rib spalling near the southwest corner of the study pillar at Site A. Colored areas indicate fallen material.

Site B will only focus on the top level and there are no change detection scans available at the time of this publication. Mining is not occurring on the top level near the instrumentation site, so any damage that occurs on the top level would likely be due to a changing stress state from undermining or a time-dependent phenomenon, such as weathering. The patterned overlap of pillars should produce stress concentrations in predictable locations, which would make it possible to differentiate localized stress-driven displacement from widespread or seemingly random displacements.

Site A Seismic Monitoring

Initial results do not show as much microseismic activity as was expected given the experience of Gangrade et. al. (13) with a very similar monitoring procedure. The difference is likely due to the lack of failure-inducing stress concentrations near the seismic sensors. Event processing is ongoing, but for the month of January, an average event rate of 8-9 events/day has been recorded with the exception of two very high event-count days which may be due to equipment noise. These events were spread throughout the monitoring area but are more prevalent in areas that are being actively mined. Figure 9 shows the cloud of located seismic events, centered around the area being undermined in January 2019. About 1/3 of the events recorded have been located in the interburden, and only a few have been located inside the instrumented pillar.

Processing of data will continue with a focus on areas that show correlating seismicity and damage or seismicity and stress. The numerical modeling shown earlier, related to Mine B, highlights the significant increase in rib stresses when pillars are offset. If damage is observed on a rib that corresponds with undermining and shows seismic activity, it is most likely going to be caused by that elevated rib stress shown in the modeling. This should provide some indication of how sensitive pillars may be to small offsets to their columnization.

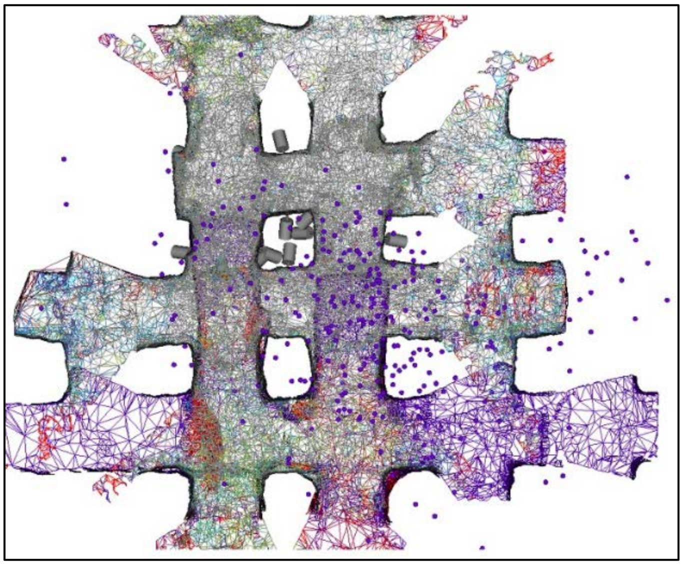

Figure 9. Purple circles represent located seismic events from January 3rd 2019 through January 21st 2019.

CONCLUSIONS

Two multiple-level underground limestone mines were instrumented and are being monitored to study stress interactions between levels. One of these mines has a thin interburden and columnized pillars, while the other has a thick interburden and offset pillars. Stress, displacement, and seismic monitoring are occurring in tandem to capture any kind of response in the rock masses on an undermined upper level.

To date, Site A does not show a large interaction between the levels, although minor spalling has been occurring and stress through a pillar in the top level has responded to mining on the lower level.

Site B has not been undermined yet, but numerical modeling predicts that very little change will ever be observed in the stressmeters, because the levels are very far apart. The mine will continue to be monitored for the small changes that are expected to occur and to verify the expected non-interaction.

The interaction between levels in a multiple-level mine is an important ground control consideration for both interburden and pillar stability. As part of this NIOSH research project, both sites will continue to be monitored throughout undermining, to explore multiple level interaction and ultimately improve our understanding of pillar loading conditions and ensure safe pillar design.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

REFERENCES

1. Newman, D., “Roof control, pillar stability and ground control issues in underground stone mines.”, *Mining Engineering.*, vol. 69, no. 8, 2017.

2. Esterhuizen, G. S., D. R. Dolinar, J. L. Ellenberger, and L. J. Prosser, “Pillar and roof span design guidelines for underground stone mines”, *Department of Health and Human Services (NIOSH), Pittsburgh, Publication*, p. 75, 2011.

3. Esterhuizen, G. S. and M. M. Murphy, “Mining Product: S-Pillar - Software for Stone Mine Pillar Design Version 1.2. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for

Occupational Safety and Health," 2018. [Online]. Available: https://www.cdc.gov/niosh/mining/works/coversheet1817.html.

4. Newman C., D. Newman, and R. Dupuy, "The Development of a Multiple Level Underground Limestone Mine from Geology Through Mine Planning", in *38th International Conference on Ground Control in Mining*, 2019, pp. 116–121.
5. Mark, C. and R. J. Tuchman, "Proceedings: New Technology for Ground Control in Multiple-seam Mining", Pittsburgh, PA: U.S> Department of Health and Human Services, Centers for Disease Control and Prevention, National institute for Occupational Safety and Health, DHHS (NIOSH Publication No. 2007-110, *Information Circular 9495*, 2007.
6. Hsiung, S. M. and S. S. Peng, "Design guidelines for multiple-seam mining, part II", *Coal Min. Process. States)*, vol. 24, no. 10, 1987.
7. Haycocks, C. and Y. Zhou, "Multiple-seam mining: a state-of-the-art review", in *Proceedings of the Ninth International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University*, 1990, pp. 1–11.
8. Hedley, D. G. F. "Design guidelines for multi-seam mining at Elliot Lake", Department of Energy, Mines and Resources, Ottawa, Ontario, Canada, Canada Centre for Mineral and Energy Technology 1978.
9. Stearns, R. G., "Monteagle Limestone, Hartselle Formation, and Bangor Limestone: A New Mississippian Nomenclature for Use in Middle Tennessee, with a History of Its Development.", State of Tennessee, Department of Conservation, Division of Geology, 1963.
10. Slaker, B., M. Murphy, and J. Winfield, "Tracking Convergence, Spalling, and Cutter Roof Formation at the Pleasant Gap Limestone Mine using LiDAR", in *Proceedings of the 53rd US Rock Mechanics Symposium*, 2019.
11. McDowell, R. C., "The geology of Kentucky-a text to accompany the Geologic Map of Kentucky", *US Geological Survey Professional Paper 1151-H,* 1986.
12. Hoek, E. and M. S. Diederichs, "Empirical estimation of rock mass modulus", *International Journal of Rock Mechanics and Mining Sciences.*, vol. 43, no. 2, pp. 203–215, 2006.
13. Gangrade, V., B. Slaker, D. Collins, S. Braganza, and J. Winfield, "Investigating Seismicity Surrounding an Excavation Boundary in a Highly Stressed Dipping Underground Limestone Mine", in *Proceedings of the 38th International Conference on Ground Control in Mining*, 2019, p. 132.