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Principal Horizontal Stress Contributing to Massive Roof Collapse at the Subtropolis Mine

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ABSTRACT

In 2015, the Subtropolis Mine in Petersburg, OH, experienced a massive ground collapse that continues to grow over time. Horizontal stress effects have affected the roof at this operation in the past and may have played a large role in this collapse. Horizontal stress can impact the roof and floor stability and endanger the health and safety of underground stone miners. Mines experiencing damaging effects from horizontal stress typically find that the principal stress direction is the same throughout the mine and the region. At the Subtropolis Mine the principal horizontal stress direction appears to change as conditions change and differs from the regional horizontal stress, particularly near the collapse or other roof fall areas. The growth over time of this collapse and other roof falls have been captured and analyzed using geologic mapping, 3D LiDAR scanning, numerical modeling and geographic information systems like ArcGIS. Utilizing these tools to better understand site-specific conditions can be critical to reducing the potential of massive ground collapses in the underground limestone industry.

INTRODUCTION

Since 2015 there have been several massive ground collapses in the underground limestone industry. A massive ground collapse, as defined in this study, consists of broken strata partially filling multiple entries and rendering them unsafe to enter. Miners working in areas of unstable ground are at risk of serious falls of roof and rib injuries. In the most severe cases, escapeways can be blocked and a subsidence basin could occur on the surface. These massive ground collapses can occur or grow unexpectedly, and they represent a high- consequence health and safety hazard with the potential to produce serious injuries to underground mine workers.

There have been several massive ground collapses; however, the Subtropolis is one of very few where horizontal stress may have played a role. The Subtropolis Mine extracts the Vanport Limestone, which is part of the Allegheny Formation, Pennsylvanian System, and ranges in thickness from 16 to 22 ft with a mining height of approximately 16 ft and a roof span of approximately 40 ft (Iannacchione et al., 2019). Generally, the Vanport Limestone is overlain by a closely laminated, slightly weathered to weathered siltstone- sandy-shale immediate roof (Newman, 2019). The standard production pillars at this mine are from 40 ft to 60 ft in length by 30 ft wide. At the Subtropolis Mine, the Vanport Limestone includes several weak bedding planes in the roof. In order to create an adequate beam, the mine implements a primary bolting strategy of five 5-ft tensioned fully grouted resin bolts per row with 8-ft spacing and a secondary bolting strategy (typically in the crosscuts or headings adjacent to crosscuts) of 8-ft cable bolts between the fully grouted bolts. Typically, the caprock left in the roof is approximately 4 ft. The Subtropolis mine has experienced damage from horizontal stress since its opening in 2006 (Iannacchione et al., 2019).

MASSIVE GROUND COLLAPSES

Massive ground collapses have been defined as multiple entries filled with broken strata, rendering the entries unsafe to enter (Evanek et al., 2022). There are two types of massive ground collapses: massive pillar collapses and massive roof collapses. Massive pillar collapses can include zones of multiple pillars that failed and are no longer capable of supporting the overlying strata. This type of collapse can initiate with the failure of a single pillar that triggers cascading pillar failure over a wide area, causing a secondary failure of the roof as well. Massive roof failures occur when the overburden rock is not sufficiently strong to prevent unstable conditions (Evanek et al., 2022). Massive roof collapses can occur over long periods of intermittent growth.

From 2008 until 2021 there have been eight massive ground collapses with one event resulting in three injuries, none resulting in fatalities, and several were near misses. Six of these massive ground collapses were determined to be as a result of pillar failure and therefore have been defined as massive pillar collapses. One of these six is the Petersburg massive ground collapse, which occurred at a mine a few short miles from the Subtropolis Mine. The remaining two massive ground collapses were a result of a failure in the overburden, one of which occurred at the Subtropolis Mine and the other at the National Institute for Occupational Safety and Health (NIOSH) Lake Lynn Research Facility which occurred slowly from 1994 to 2006 (Figure 1). The cause of the Lake Lynn massive roof collapse has been studied and several factors are suggested including weathered joints, inadequate caprock thickness, exceedingly weak strata above the caprock, strata dips that favor strata extension into the adjacent surface quarry, freeze-thaw action in the entries near the highwall, and a lack of adequate support.

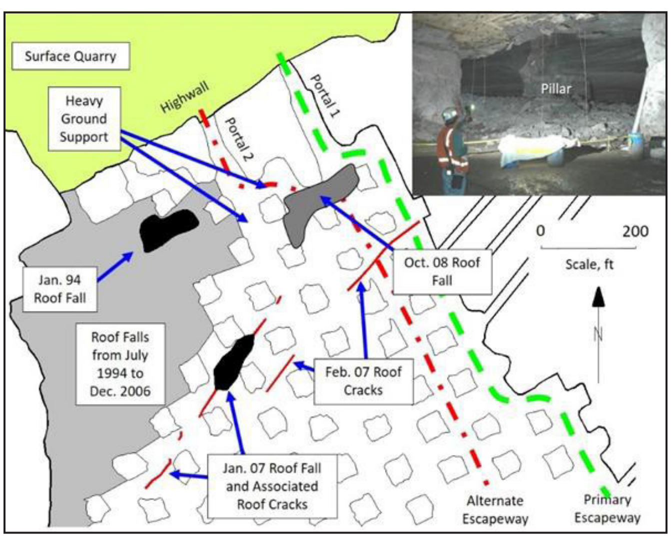

Figure 1. Location and dates of massive roof collapse at the Lake Lynn Laboratory from 1994 to 2007

The Petersburg Mine massive collapse, though located in the Vanport Limestone and only a few miles from the Subtropolis Mine, experienced very different ground conditions. The mine did not experience as many damages from horizontal stress as the Subtropolis Mine, so there was no need to adopt the stress control layout; however, the mining dimensions were very similar to most of the old workings at the Subtropolis Mine. The difference in ground conditions at Petersburg is mainly due to its weak, moisture-sensitive floor and weak bands within the pillars (Murphy et al., 2016). The collapsed pillars were able to remain stable for 10 years after mining. Adding moisture or repeated wetting and drying may have caused further weakening of the floor under these pillars, leading to the initiation of the pillars punching into the floor after 10 years (Murphy et al., 2016). When the pillars punched into the floor and failed, it caused an increase in loading on nearby pillars, causing them to fail in rapid succession. Since this was a failure of the pillars, occurred almost instantaneously, and created a large subsidence basin at the surface with no remnant pillar humps, this collapse is defined as a massive pillar collapse. Massive roof collapses can be less dramatic and occur over a larger span of time; however, they can still represent a significant ground control hazard.

UNDERSTANDING CHANGES IN PRINCIPAL HORIZONTAL STRESS DIRECTION

The massive ground collapse at the Subtropolis Mine in Petersburg, OH, is also defined as a massive roof collapse. The failure of the roof began in late 2015 and has slowly developed over time and now encompasses several entries in the north-central part of the mine (Figure 2). The Subtropolis Mine, which is a room-and- pillar mine that extracts the Vanport Limestone, has a long history of reacting to horizontal stress damage in the roof. Since the mine opened in 2005, the operators have changed the orientation of the mine several times in order to alleviate the detrimental effects of high horizontal stress and to determine the principal horizontal stress direction (Figure 3).

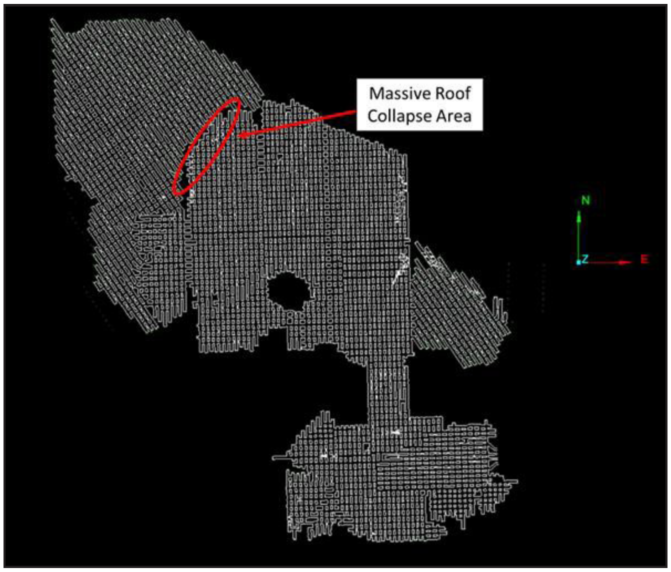

Figure 2. Subtropolis Mine Map with massive roof collapse area circled in red

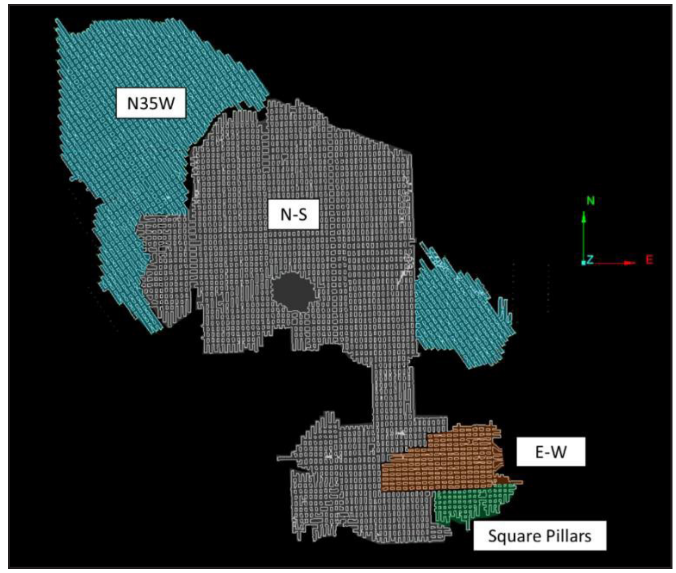

Figure 3. Subtropolis Mine Map with varying heading orientations

Typically, a mine will find the orientation of the principal horizontal stress at or near to the regional horizontal stress. At the Subtropolis Mine, the principal horizontal stress differs from the regional horizontal stress and can even differ across the mine itself. Evidence to support these changes in the principal horizontal stress direction come in the form of cutter roof failures and oval-shaped roof falls oriented in different directions in specific areas of the mine. The principal horizontal stress direction at this mine tends to be generally N35W.

Roof falls at this mine fit the same characteristics of examples of high horizontal stress found at other limestone operations. Roof instabilities typically begin with the development of compression zones consisting of low-angle shears in a consistent orientation. When the roof falls occur, many of them are oval in shape with the long axis oriented in the same direction as the shears (Iannacchione et al., 2001). Figure 4 details the mechanism of failure typically seen at Subtropolis Mine. When layered strata are subjected

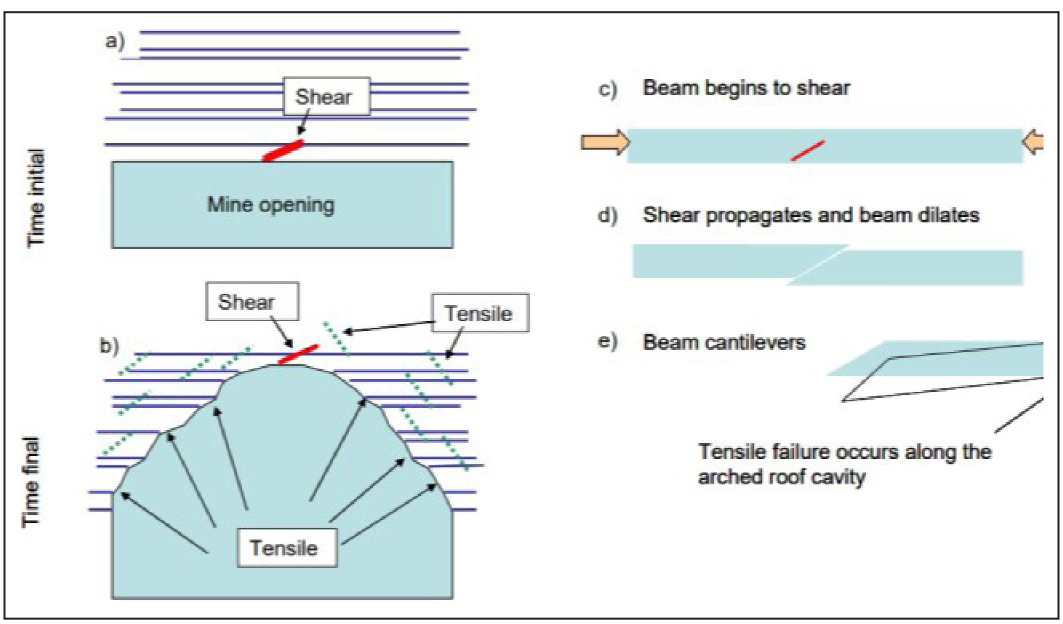

Figure 4. Generalized sequence in which individual roof beams fail and develop into large roof falls under elevated horizontal stress conditions (Iannacchione et al., 2005)

to excessive lateral loads, it can buckle under compressive stresses, failing in shear (Iannacchione et al., 2019).

Failures appear to originate in the lowest beams, or the beams closest to the mine opening due to the concentration of stresses in the lower beam and constraints to bending in the upper beams (Iannacchione et al., 1998). Therefore, failure begins with a shear in the first foot of the caprock. Shear failures appear as low- angle ruptures in the rock with a kind of "rock flour" along the newly created surface (Iannacchione et al., 2019). Then, the shear propagates, and the beam begins to dilate. Next, the beam begins to cantilever, causing tensile failure along the boundary between the roof and the pillar. Once the beam fails completely, the shear failure propagates to the next layer. In other mines the shear failure continues to propagate upwards through the roof layers until the fall has developed an arch shape. However, at the Subtropolis Mine there are very weak shales present above the caprock. Here, once the caprock fails, the fall takes on a chimney shape and, in some cases, extends approximately 30 ft into the roof.

Figure 5 shows 3D LiDAR scans capturing the shape of this type of fall and its growth over time (shown in red). In this roof fall, the failure extends approximately 30 ft into the roof and up into the overlying coal seam. The shear failure orientations are parallel to the long axis of the elliptical-shaped cavities in this case study. All of these damages have been captured using detailed geologic mapping and, in some cases, 3D LiDAR scanning. For example, Figure 6 contains two photos from the Subtropolis Mine. Photo A is an example of a dilating beam and Photo B shows shear failure in three separate fully-grouted bolts from the same area.

The operator noticed that these types of failures in the N-S entries appear to concentrate at the northwest and southeast corners of the pillars. In order to minimize the number of these types of roof failures, the mine utilized the stress control layout. The stress control layout utilizes headings in the principal horizontal stress direction. This minimizes damage to the headings but concentrates damage into the crosscuts. To minimize damage to the crosscuts, the mine has implemented the use of rectangular pillars. The mine also has implemented a secondary bolting strategy and included windows in every other crosscut. According to Evanek et al. (2020), "Windows are used to resist horizontal movements or deformation that occur parallel to the maximum horizontal stress direction or perpendicular to the direction of stress failures. A window is developed by leaving an increased thickness of roof rock in the crosscuts, thus reducing the crosscut dimensions

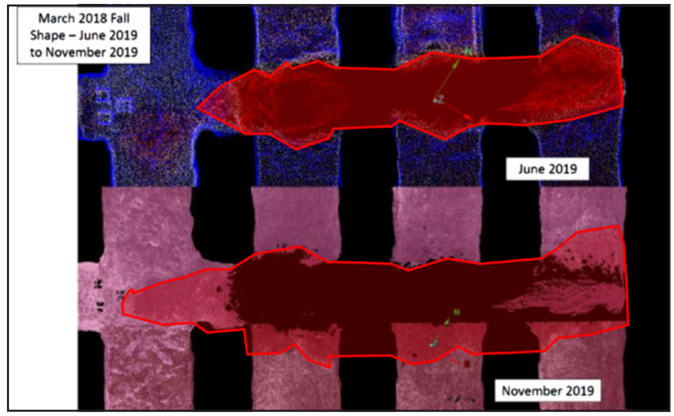

Figure 5. March 2018 roof fall in XC02 progression from June 2019 to November 2019

Figure 6. A) Photo of shear failure in roof and B) Photo of sheared bolts

vertically." The first time the stress control layout was implemented at the mine was in the northwestern region of the mine in 2018, on the other side of the massive collapse area. Numerical modeling was utilized in this study to confirm damage patterns seen at the mine. The model, as seen in Figure 7, maps the distribution of the maximum principal horizontal stress over two different mine layouts at Subtropolis. The principal horizontal stress in this model is parallel to the Y-axis in the figure at N35W. The pillars with a N-S orientation show a higher concentration at the corners of the entry (indicated by red), which aligns with damages mapped underground. The pillars oriented parallel to the principal horizontal stress at N35W show damage (indicated by red) being concentrated at the crosscuts and not in the entries. This damage concentration has also been mapped at Subtropolis and also confirms the stress control layout is working as planned.

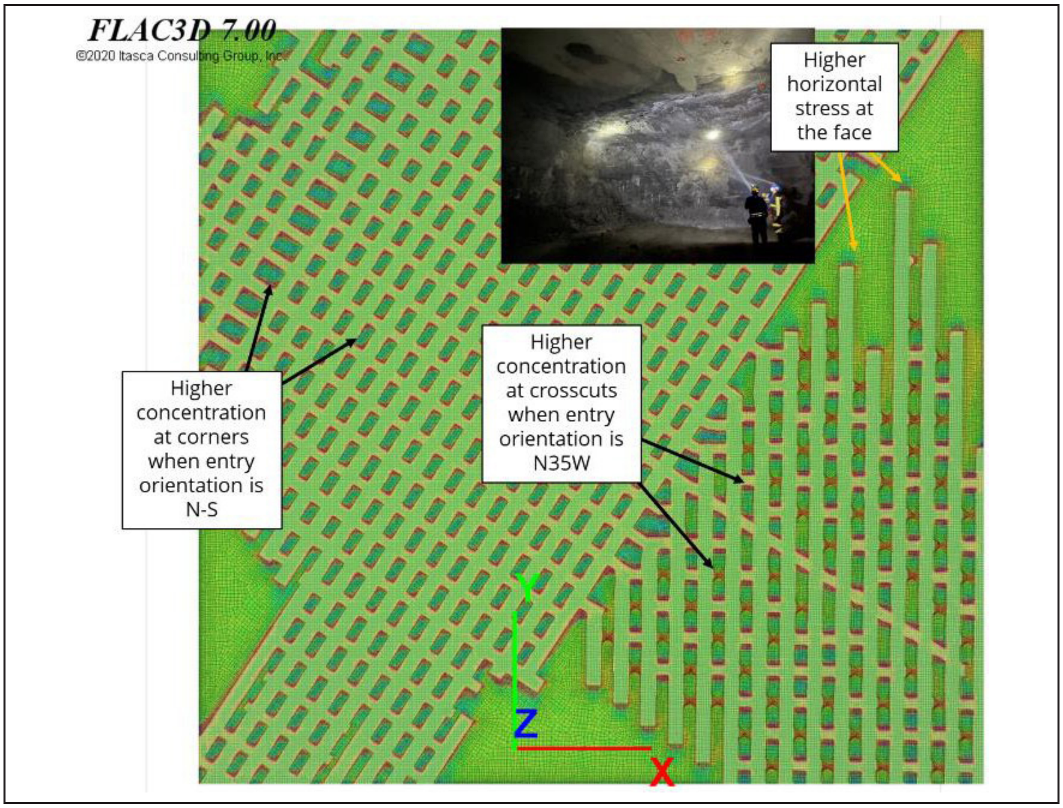

Figure 7. Model of distribution of maximum principal horizontal stress

THE SUBTROPOLIS MASSIVE ROOF COLLAPSE

In 2015, a massive roof collapse at Subtropolis Mine began to form in the northwestern portion of the mine. From April of 2016 to the end of 2018, the collapse area had been relatively quiet. However, in 2019, mining began to extend close to the old workings where the collapse had occurred. Instabilities began to form again, and the size of the collapse began to grow. In addition to its growth in the old workings, new damages began to "jump" into the new workings, causing a major roof fall in one of the crosscuts nearest to the old workings and with the lowest caprock thickness (Figure 8). Since mining moved further from the edge of the collapse area, damages were expected to stop. However, due to the presence of horizontal stress at this mine, the collapse has not stopped progressing further into the roof and outward into the open entries. The operator had witnessed the role horizontal stress played in the collapse. Damages progressed slowly as cutters began to run from east to west from the collapse area and the operator was able to follow the shifting of the test holes as it went. 3D LiDAR scanning was able to capture some of these changes over time.

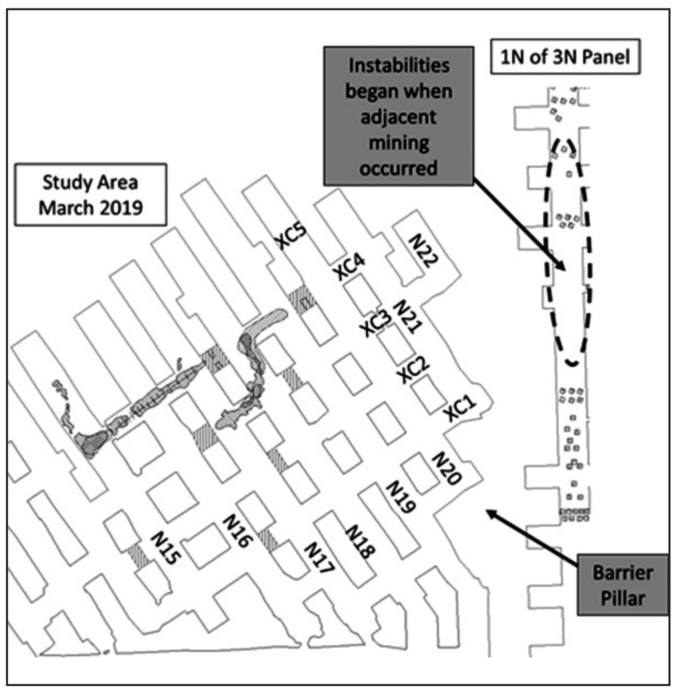

Figure 8. a1N of 3N Panel location in relation to mining in 2019 (Evanek et al., 2020)

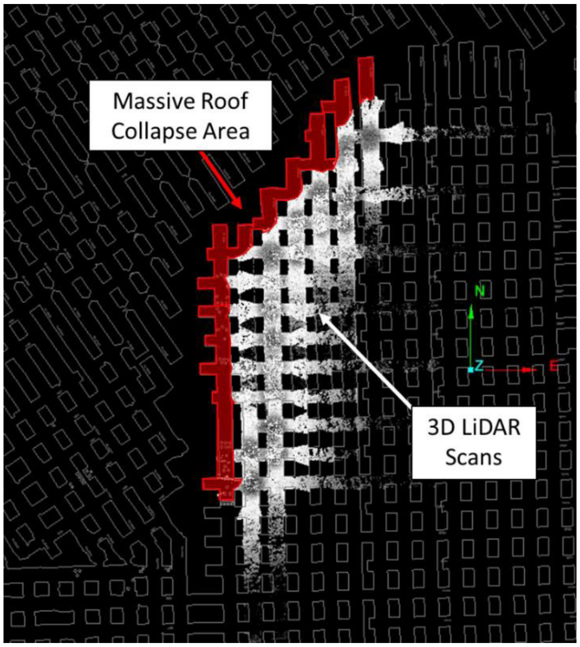

Figure 9. 3D Lidar pointcloud ariel image of massive roof collapse

Baseline 3D LiDAR scanning of the collapse area was conducted in July of 2022. Scans were captured using the Maptek I-Site 8200 stationary scanner, and 360-degree scans were collected at each entry and crosscut along the collapse area approximately 50 ft apart. Each scan was then registered to each other using Maptek's PointStudio program and georeferenced to the Subtropolis Mine map. This allowed researchers to visualize the collapse area (Figure 9). Figure 10 shows two images of the baseline pointclouds at a mine level view. Under a previous research project, the southern portion of the collapse area had been scanned prior to the majority of the failure. This acts as a very early

baseline scan for that particular part of the collapse area. These baseline scans have been compared to other scans collected at later dates to look for the amount of change over time. Over the course of this study, changes have been seen in two portions of the collapse area. One area is the southern portion of entry N3N2, and the other is the northernmost portion of entry N3N7.

The northernmost portion of entry N3N7 as shown in Figure 11 saw changes to the rib and to the roof from July 2022 to October 2022. A separation of the lower layer of limestone in the roof occurred around a concrete crib. A large fracture opened up around the concrete crib and perpendicular to the entry. The southern portion of entry N3N2 saw significant changes to the west in the N3N1 entry, which was inaccessible to scanning in July 2022.

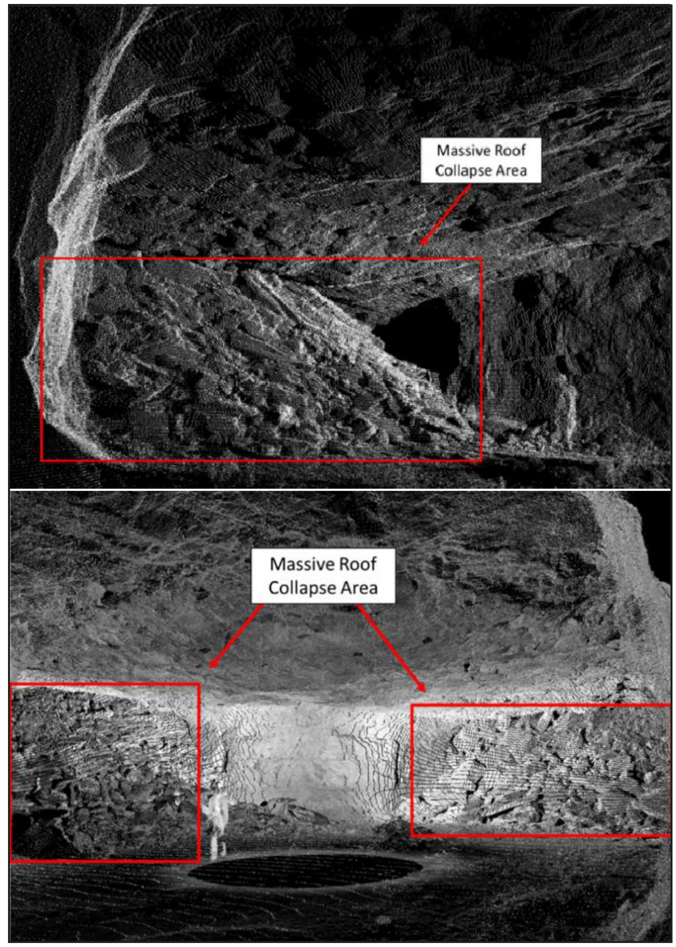

Figure 10. 3D LiDAR pointcloud images of the massive roof collapse at mine level

However, scan data from a previous project had been collected in June 2019.

Therefore, July 2022 scans could be compared to June 2019 scans in entry N3N2. Changes were detected in the roof of N3N2 at an angle perpendicular to the principal horizontal stress direction as shown in Figure 12.

GROUND FAILURE MAPPING

In order to map areas of current and potential ground failure across the Subtropolis Mine, researchers utilized geologic mapping conducted by the operator and analyzed the data using ArcGIS. Researchers found that certain characteristics or indicators were deemed the most important when trying to predict areas of instability at the Subtropolis Mine. Table 1 lists the indicators used in this study and the ratings used to map these hazardous areas. The first indicator is the orientation of the headings at the Subtropolis Mine. Two major orientations were used, the North–South

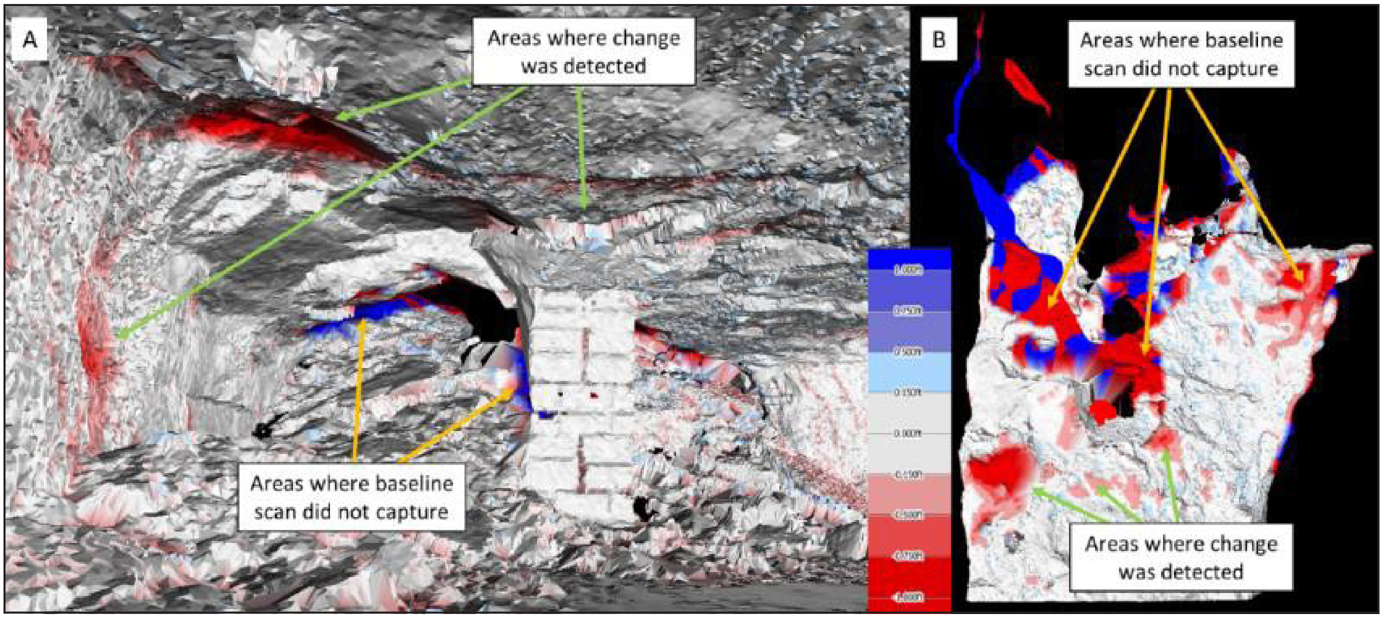

Figure 11. Changes over time in N3N7 from July 2022 to October 2022 (Red represents material removed and blue represents material added) A) In mine view B) Ariel view

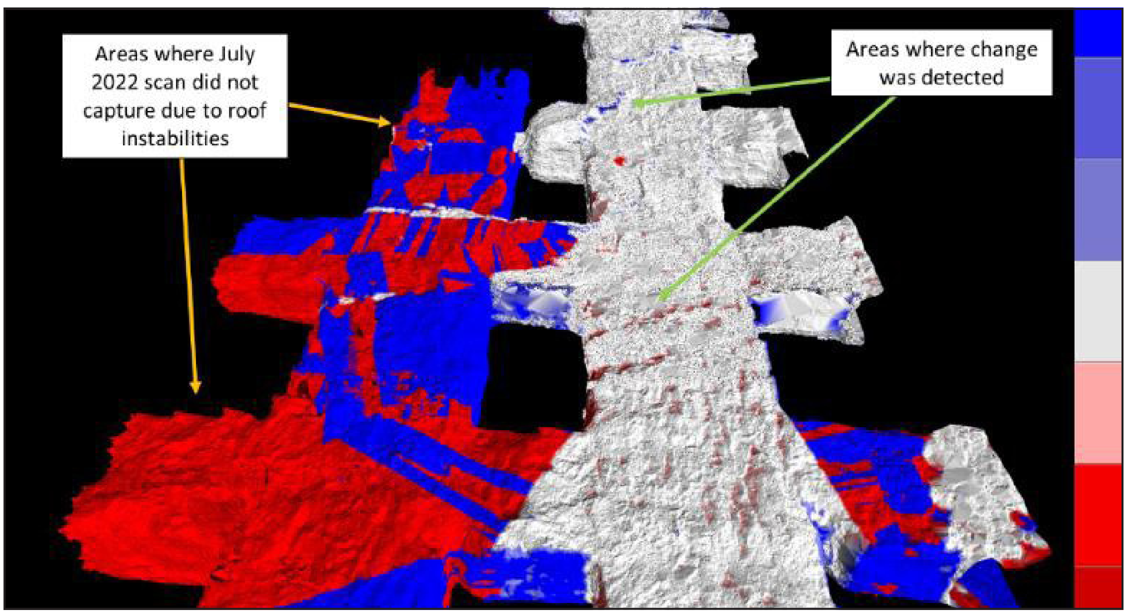

Figure 12. Ariel view of N3N2 changes over time from June 2019 to July 2022 (Red represents material removed and blue represents material added)

Table 1. Indicators of Potential Ground Failure

Indicators	Good	Bad
Heading Orientation	N35W	N-S
Overburden	Less than 140 ft	Greater than 140 ft
Distance to Stream Bed	Greater than 200 ft	Less than 200 ft
Distance to Joint and Clay Vein	Greater than 100 ft	Less than 100 ft
Caprock Thickness	Greater than 36 in	Less than 36 in

orientation which typically saw more instabilities and roof failure, and the N35W orientation which is aligned parallel to the principal horizontal stress direction and typically saw less instabilities and roof failure. The second indicator is overburden, which was estimated as problematic at greater than 140 ft. The third indicator used was distant to stream beds. A 200 ft buffer was utilized, which is typically used in coal to account for the influence of a stream bed on mining conditions. Researchers also implemented a 100 ft buffer around joints and clay veins and use caprock thickness data tracked from test holes approximately every other crosscut within the mine.

Caprock thicknesses less than 3 ft were categorized as hazardous.

The AutoCAD version of the mine map that included the mine outline and the indicators listed above was imported into ArcGIS where a hazard map was produced (Figure 13). This map was produced without previous knowledge of the location of roof failure or the massive roof collapse. However, the map was able to indicate a potential for ground failure right over the massive roof collapse region. This may indicate that heading orientation,

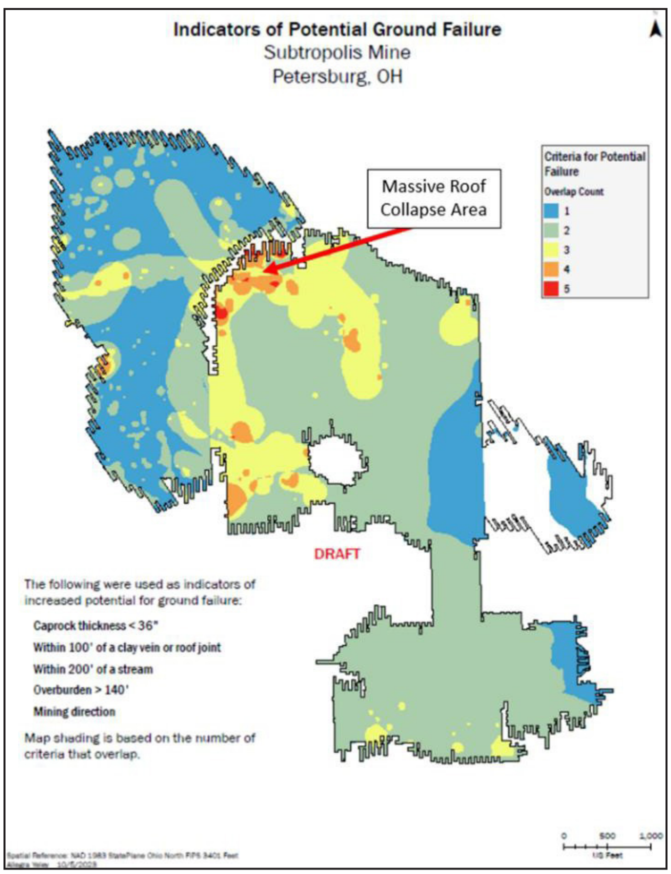

Figure 13. Indicators of Potential Ground Failure Map of the Subtropolis Mine

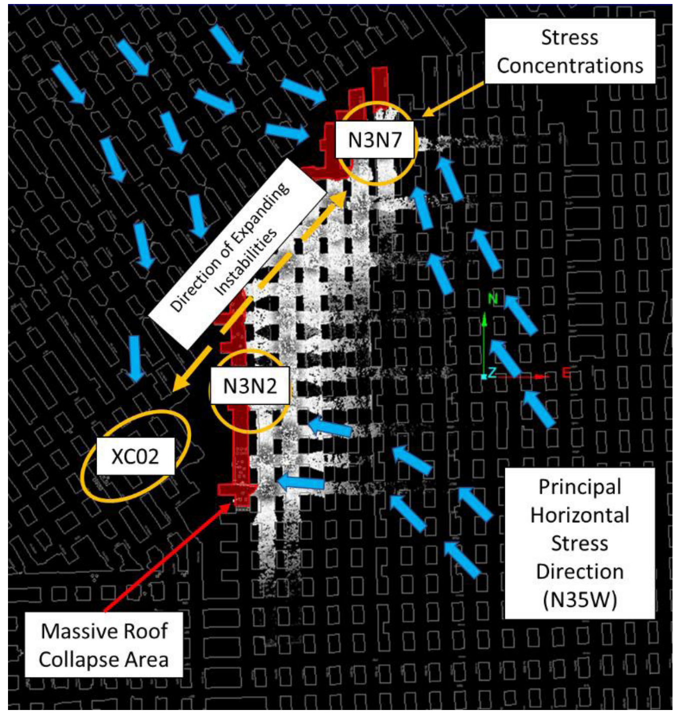

Figure 14. Ariel view of expected principal horizontal stress directional changes and concentrations around the massive roof collapse

overburden, stream beds, joints, clay veins, and caprock thickness might be leading factors in the cause of this massive roof collapse. The hazard map was also able to correctly map a hazardous area in the southwestern part of the mine, where a large roof fall occurred. This area had crisscrossing clay veins in the overlaying shale with several fractures in the roof and a constant flow of water prior to the fall. Cutter roof failures and rock flour were present during the failure as well indicating the shear failures as discussed in Figure 4. According to the operator, the Lower Kittanning Coal Seam may have also rolled down towards the top of the Vanport in this area.

SUMMARY

The massive roof collapse at Subtropolis Mine is still expanding slowly over time. Geologic mapping and 3D LiDAR scanning showed that instabilities are expanding relatively quickly perpendicular to the principal horizontal stress direction and expanding relatively slowly parallel to the principal horizontal stress direction (Figure 14). Strata failures around the margins of the collapse area can reinitiate depending on the proximity of the mining front.

Researchers were able to utilize detailed geologic mapping provided by the operator to map areas of potential ground failure in ArcGIS. Results indicated that heading orientation, overburden, stream beds, joints, clay veins, and caprock thickness might be leading factors in the cause of this massive roof collapse. Several of these factors overlap at or near the collapse area, including heading orientation, prominent clay veins and a close proximately to a stream bed. However, it is likely that heading orientation and horizontal stress damage is the primary driver of the failure and is continuing to cause the slow expansion over time of the collapse area.

This case study is presented to help better understand how massive roof collapses could result from lateral strata movement. Lessons learned from the Subtropolis Mine could provide the underground stone mining industry a unique insight into how massive roof collapses develop, which will assist with recognition in similar environments to improve the health and safety of underground miners.

LIMITATIONS

This study was conducted at one case study site and is not intended to be applied to all mines with or concerned with massive ground collapses. Rather, lessons learned from this case study, the tools used to understand the mechanisms of failure, and the engineering controls implemented by the mine to prevent further instabilities are presented to aid other underground limestone operations in developing a better understanding of massive ground collapses and the role geologic conditions and mine design may have in the cause and prevention of these hazardous events.

Limitations also apply to the Indicators of Potential Ground Failure Map in Figure 13. Researchers gave the same weight for all parameters. However, some parameters could be more substantial than others and still other parameters could not be represented at all.

This is a qualitative analysis, and the relative importance of each parameter is outside the scope of this study.

DISCLAIMER

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

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