Evaluation of stress-control layout at the Subtropolis Mine, Petersburg, Ohio

Anthony Iannacchione\textsuperscript{a,}, Tim Miller\textsuperscript{b}, Gabriel Esterhuizen\textsuperscript{c}, Brent Slaker\textsuperscript{c}, Michael Murphy\textsuperscript{c}, Natalie Cope\textsuperscript{b}, Scott Thayer\textsuperscript{d}

\textsuperscript{a}Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15216, USA
\textsuperscript{b}East Fairfield Coal Company, North Lima, OH 44452, USA
\textsuperscript{c}National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Mining Research Division, Pittsburgh, PA 15236, USA
\textsuperscript{d}Mine Vision Systems Inc., Pittsburgh, PA 1520, USA

Abstract

The Subtropolis room-and-pillar mine extracts the Vanport Limestone (Allegheny Formation, Pennsylvanian System) near Petersburg, Ohio. Strata instability problems associated with excessive concentrations of lateral stress caused the mine operator to implement a change in layout design. This mining method has been identified as a stress control layout and has been used by other underground stone mines in the past with varying degrees of success. Practical experience has shown that entry headings advance in the direction of the principal lateral stress, producing lower stress concentrations with better mining conditions. It is important to minimize stress concentrations along the mining front, so an arrow-shaped advance is recommended. This technique advances more developments (headings) in a “good” direction and reduces developments (crosscuts) in the “bad direction.” As is expected, the stress control layout enhances the potential for shear failures in crosscuts. It is, therefore, important to focus crosscut engineering interventions that either: (a) lower stress concentrations (for example, an arched roof) or (b) enhance strength of the strata containing the shears (for example, rock reinforcement). This study focuses on observing strata conditions on a regular basis and monitoring the response of these strata to changing geologic and mining conditions through 3D Dynamic LiDAR scans.

Keywords

Horizontal stress; Stress-control layouts; Underground stone mines
1. Introduction

1.1. Project aims

The Subtropolis Mine is extracting the Vanport Limestone in northeastern Ohio. Since the start of mining in 2006, ground conditions have been significantly affected by excessive lateral stress condition. In some other mining districts with this hazard, certain mine layouts have been shown to lessen the potential for unstable ground conditions. The term “lessen” is used to state the realization that stress concentrations are not eliminated but instead occur in less frequency and intensity, and their locations can be projected.

The stress-control mine layout, specifically for large-opening room-and-pillar stone mines, naturally evolved at mines suffering from excessive lateral stress problems. These mines will typically experiment with methods to mitigate adverse impacts, thus developing best practices for their conditions. These practices have evolved into a basic framework for the stress-control mine layout. For example, Jack Parker was able to write about personal experiences at the White Pine Mine in Michigan [1,2]. Various researchers at the U.S. Bureau of Mines (USBM), the Mine Safety and Health Administration (MSHA), and the National Institute for Occupational Safety and Health (NIOSH) have studied the effectiveness of stress-control mine layouts over a wide range of geologic conditions [3–5]. While the stress control layout design approach has proven successful at several underground stone mines, it can be difficult to implement. For example, excessive stress conditions in crosscuts can put the ground control focused intervention at odds with ventilation and haulage constraints, thus limiting optimal crosscut size, shape, and location. Therefore, more information on the effectiveness of this approach is needed.

Mine layouts with the purpose of mitigating the impacts of high lateral stress are needed so that safe working conditions can be realized in the underground stone mining industry. While stress control layouts have been implemented at various operations, quantitative data have never been collected to measure the enhanced performance. It is also recognized that performance data is influenced by unique geologic and mining conditions. Therefore, what works at one site may need some level of modification to work successfully at another site.

1.2. Method of study

After encountering difficult ground during developments in 2017 (Fig. 1), the East Fairfield Coal Company (EFCC), operators of the Subtropolis Mine, began implementing a new stress control mine layout. This paper details the positive aspects as well as the challenges in implementing this design technique.

To help document and analyze the implementation of the stress control mine layout, a cooperative research project was undertaken jointly by NIOSH and EFCC. This project relies on detailed in-mine observations by mining company geologist and NIOSH engineers as well as 3D Dynamic LiDAR scans (by Mine Vision Systems) that document mining conditions during the study. Trends from these observations are used to determine the efficiency and effectiveness of different engineering interventions in the aim to better control the workplace environment found at many underground stone mines.
2. Background

The Subtropolis Mine has rooms 9.1–12.2 m wide and pillars with length-to-width ratios ranging from 1.5 to 2.5. The Vanport limestone ranges in thickness from 4.9 to 6.7 m, so only development mining is used. The nominal extraction height is 4.9 m. There are several other Vanport limestone mines to the east, one in Ohio, and the remainder in Pennsylvania (Fig. 2). Several of these mines, including Petersburg, Annandale, and Winfield, have had a history of ground control issues related to excessive concentrations of lateral stress.

2.1. Roof falls dominated by shear failures

In conditions of excessive levels of lateral stress, the highest stress concentrations will produce shear failures and can form unstable roof areas (Fig. 3). When layered strata are subjected to excessive lateral loads, it can buckle under compressive stresses, failing in shear. This type of behavior has been well documented in Pennsylvania and Ohio limestone mines [6,7]. Shear failures appear as low-angle ruptures in the rock with a kind of “rock flour” along the newly created surface (Fig. 3). These surfaces are typically serrated and can be sharp, forming at angles averaging 15° with the layer’s bedding planes. The strike orientation of these shear surfaces is typically perpendicular to the principal stress direction. When roof fall forms under these conditions, they can contain dozens to hundreds of shear failures. We know this because the formation of shears has been identified with micro-seismic technology [8]. Roof rock weakened by these failures can be unstable and often shear failures continue to form until a stable arch is formed in the main roof. This problem is particularly hazardous when failures propagate into the overlying shale rock. As shown in Fig. 3, the shear failure orientations mirror the long axis of the elliptical-shaped cavities. In-mine observations confirm that shear failures are occurring perpendicular to the orientation of the maximum horizontal stress field.

2.2. Recognizing excessive levels of lateral stress in stone mines

Recognizing unstable roof conditions related to high lateral stresses can be difficult, especially when examining mine maps without the benefit of face positions. An example of this is shown in Fig. 4a where roof falls appear to be random until the individual falls are compared to outlines of the mining front. If excessive levels of lateral stress are causing the unstable ground conditions, roof falls will be located at the point protruding into the highest stress concentrations (i.e., perpendicular to the orientation of the maximum horizontal stress field) [9]. Roof falls associated with excessive lateral stress typically occur as mining advances into unmined rock perpendicular to the orientation of maximum lateral stress. Once the fall occurs, stress is temporarily relieved.

2.3. Stress control mine layouts for stone mines

One potentially safer way to room-and-pillar mine in a directional lateral stress field is to utilize stress control techniques [1,2,6]. These techniques are listed below and illustrated in Fig. 4b: (1) maximize the number of headings driven parallel to the direction of maximum horizontal stress; (2) reduce the number of crosscuts driven perpendicular to the stress field; and (3) maintain a wedge-shaped mining front parallel to the direction of maximum horizontal stress.
It should be noted that a stress control mine layout does not eliminate all stress-related strata conditions. In fact, stress damage is concentrated within crosscuts. To help offset this problem, the following techniques have been tried, with varying degrees of success, within crosscut entries of stress control mine layouts: (1) drive crosscut faces only into an existing heading, and it should also be noted that waiting too long to develop the crosscut can enhance shear failure frequency, so the heading should not be more than 15.2–30.5 m past the breakthrough point; (2) offset crosscuts to create only three-way intersections; (3) reduce the width and length of crosscuts; (4) lower room height; (5) form an arch within the crosscut roof, and (6) add additional support and extend this support into the adjacent intersections.

2.4. Early mining at Subtropolis

In 2007, several of the authors examined mine layouts at different points in time and compared them with roof falls that occurred within a few months of the outline date (Fig. 5). Three different mine layouts are shown: (1) the October 2006 map shows two falls in the headings (East-West, E-W, oriented entries) (Fig. 5a); (2) the March 2007 map shows several roof falls along the north-west mining front (Fig. 5b); and (3) the December 2007 map shows a very significant roof fall along the northern most entries and north-west mining front near the most western entries (Fig. 5c).

In 2007, the orientation of the stress field was thought to be closer to north–south (N-S). EFCC decided to reorient the Subtropolis mine layout (Fig. 5c), resulting in headings advanced N-S as opposed to E-W (prior orientation). When rectangular pillars are used, the headings are the dominant entry orientation. That layout design, N-S headings, was used until February 2018 with varying degrees of success.

3. Stress control mine layout at Subtropolis mine

During the closing months of 2017, conditions within mining developments deteriorated, causing several headings to be idled (Fig. 6). At one point, nine of the thirteen headings were idled. Mine personnel observed roof shears with their associated rock flour and found the orientation to average ~N 55°E (Fig. 7). As stated earlier, shears are generally oriented at right angles to the direction of lateral movement, so the direction of the principal lateral stress should be ~N 35°W. Mine personnel confirmed this observation by examining the offset of strata within open roof exploration boreholes (Fig. 7). Strata movement directions average ~N 35°W. Both of these data confirmed the orientation of the principal lateral stress to be ~N 35°W.

NIOSH was contacted in January of 2018 by EFCC to conduct an independent investigation so that others might benefit from the Subtropolis experience. EFCC and NIOSH agreed to document the effectiveness of this significant change in mine layout to help mitigate the damaging effects of excessive levels of lateral stress. In particular, an effort would be made to document the effectiveness of this new stress-control mine layout on the overall stability of the strata.
3.1. Current status of project

Since late February 2018, detailed information on the conditions of the strata within the study area have been observed both by EFCC and NIOSH personnel and measured by an independent contractor with 3D Dynamic LiDAR scanning technology. Fig. 8a shows the entries developed from February 27 to December 6, 2018. While the project is planned to continue, the quality and quantity of the data warranted the decision to report on current findings. During this time period, the mine operator has driven all of the headings in the ~N 35°W direction. As expected, crosscuts have sometimes proven a challenge and have required testing of different engineering interventions.

3.2. Condition of the headings

As stated earlier, the principal objective of the stress control mine layout is to drive more developments parallel to major lateral stress (good direction) and less developments perpendicular to major lateral stress (bad direction). This is how the headings at Subtropolis have been developed (Fig. 8b). The use of rectangular pillars with length-to-width ratios ranging from 1.5 to 2.7 result in heading developments exceeding the crosscut developments by this same factor. In addition, Subtropolis was successful in developing an arrow shape to their mining front.

Fig. 9 provides examples of the conditions found in headings within the study area. In general, these roof strata, while containing an array of natural, blast, and stress-related fractures, are thought to be free of stress-related shear failure and the associated roof falls.

3.3. Condition of the crosscuts

As expected, the strata stability challenges have all occurred either within the crosscuts or, on occasion, at the intersections adjacent to these crosscuts. Some crosscuts have remained stable and required only planned scaling and nominal rock reinforcement. However, when crosscuts begin to develop shears, it is possible they can propagate until stress concentrations are lowered or rock reinforcement increases roof strata strength. The first example of this happened from early May to early June 2018 (Fig. 10). The initial roof shears occurred on May 1 in a crosscut that showed signs of high stress during development. The shear failures first propagated to the northeast, stopping within an adjacent crosscut. During this same period, shear failures also propagated to the southwest, extending through the adjacent crosscut and terminating in a heading containing secondary support. This area eventually began to stabilize as developments extended further to the northwest.

The second major crosscut instability occurred from July through September 2018 (Fig. 11). The roof shears first appeared in the outside entries along the southwest and northeast portions of the unstable roof rock trend (Fig. 11, pictures (a) and (c)). The trend was some 90–120 m to the northwest of the May/June 2018 crosscut instability. Several of the crosscuts in this trend showed signs of excessive stress (shear development, rock fracturing noise, etc.) and were driven with modified blasting patterns that promoted an arched roof. They were also heavily supported with secondary rock reinforcement.
3.4. Techniques to stabilize the crosscut

The two most common control techniques for crosscuts with instabilities were to apply secondary rock reinforcement and to arch the roof (back). The secondary support consisted of adding a row of 2.4 m cable bolts on spacings of 2.4 m between the primary support of 1.4 m point-anchored tension bolts on 2.4 m spacing (Fig. 12). This combination of 1.4 m point-anchor tension bolts with 2.4 m cable bolts was effective in containing the unstable strata and preventing the roof from failing above the limestone roof member and into the overlying shale layers.

Another technique was to arch the roof. Arching of the roof eliminates sharp corners where stresses can concentrate. Crosscuts in the study area are often arched. The arch roof technique was marginally effective in controlling shear developments. The mine operator tried several different blasting techniques and patterns to help form a stable arch roof (Fig. 13). Shooting the top holes at the same time can sometimes result in less fractured roof.

Crosscut angles have also been altered to help identify an orientation that is less than 90° to the principal lateral stress direction. However, haulage concerns were found to override the strata control benefits of angled crosscuts. Lastly, crosscut space increases were attempted to lower the amount of mining in the bad direction. But here again, ventilation and haulage concerns have limited crosscut spacing under normal conditions to a range of 15–18 m. This has reduced the nominal length-to-width ratio of the rectangular pillars to ~1.5.

4. 3D Dynamic LiDAR Scans

3D Dynamic LiDAR scans were conducted at three different time intervals (May 3, August 16, and December 6, 2018). This scanning technology consists of three primary components: a LiDAR scanner, color camera, and a lighting system (Fig. 14a). Twelve initial scans occurred on 3 May 2018 in headings out by the active faces, moving forward with assistance of a front-end loader at a slow walking pace until the advancing face was encountered (Fig. 14b). At that point, the front-end loader backed away from the face until the starting point was encountered. The scanning equipment is positioned roughly in the center of the entry and transported toward the twelve working faces. Fig. 14c shows that the global roof elevation changes by approximately 3.7 m over the study area in response to new developments. It also shows some localized changes in roof elevation. In some cases, these rapid, local changes in roof elevation align with roof falls and shear failures. The local changes were compared with roof observation maps and showed good agreement.

While the LiDAR scans are still being analyzed and a full report will be forthcoming, it is possible to demonstrate the utility of this technology in characterizing the performance of the mine openings to changing lateral stress conditions. For example, XC37 was mined until January 2018 (Fig. 14). At that point, roof instabilities made additional mining difficult. The condition of both the roof and floor within XC37 is shown in Fig. 15. This data demonstrates the level of stress impacting XC37. The initial May 3, 2018 scan of the study area demonstrated pronounced roof failures related to extensive shear failures. In addition, floor cracks are superimposed on floor elevation maps showing that the cracking is associated with significant heaving. These images are being compared with visual observations so that
the general strata stability conditions can be assessed. These data will be used to determine the impact of the stress control mine layout with the previous layout used at the site.

5. Summary

The Subtropolis Mine has experienced varying degrees of damage from lateral stress throughout the life of the mine. This has resulted in numerous mine plan changes implemented to minimize these hazardous conditions. In early 2018, mining progress slowed due to excessive levels of lateral stress. Previous observations and studies by Jack Parker and others indicate that mine headings developed parallel to the primary lateral or horizontal stress direction exhibit the least amount of stress-related failures [1,2].

In February 2018, the Subtropolis Mine layout was turned to drive headings directly into the direction of principal lateral stress. Visual observations of roof, rib, and floor conditions have occurred over a nine-month period (March to December 2018) to locate major strata instabilities (roof shears, floor heave, etc.). These observations are being further refined by 3D Dynamic LiDAR scans of the study area.

To date, the study demonstrates the importance of mine orientation with respect to local lateral stress fields and has provided evidence that suggests the stress control mine layout can be successful in reducing strata instabilities within headings. Techniques and examples are provided in this paper detailing how site-specific and regional trends in lateral stress orientation can be understood. Mine operators should determine lateral stress conditions in order to properly orient their headings and thus improve entry stability. It was also found that the crosscuts typically require additional support and have periodically developed failures that have cut across the study areas. This paper documents techniques to better control unstable strata within crosscuts for a specific set of conditions, some of which are unique to this mine. Additional stress control measures were discussed but not implemented for site-specific reasons. Without question, this study has benefited from the meticulous collection and analysis of observational data supplemented with LiDAR scans. These techniques are being used to evaluate subtle changes in the mine’s layout and to documenting the effect of remedial measures. This analysis serves to determine the efficiency and effectiveness of important engineering intervention that, if successful, could improve the workplace environment found at other underground stone mines with similar issues.

Disclaimer

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Fig. 1.
Yearly developments within the Subtropolis Mine since it opened in 2006.
Fig. 2.
Underground stone mines operating near the Subtropolis Mine in the Maxville, Loyalhanna, and Vanport limestones.
Fig. 3.
Directional roof fall comprised of numerous shear failures in an entry driven in 2007.
Fig. 4.
Examples of how mine layout orientation can influence roof fall characteristics.
Fig. 5.
Early mine layouts with associated recent roof falls.
Fig. 6.
Conditions within the study area.
Fig. 7.
Rock flour directions observed within the Subtropolis Mine indicating average shear orientations of N 55°E, strata movement directions from roof borehole offset observations had an average orientation of N 35°W.
Fig. 8.
Mining directly into the lateral stress field.
Fig. 9.
Pictures of stable roof conditions within headings of stress-control layout.
Fig. 10.
The first significant crosscut instability, May to June 2018.
Fig. 11.
Crosscut instabilities from July to September 2018.

(a) The crosscut was developed at an oblique angle to the heading

(b) Indicates where the crosscut was advanced from both directions

(c) Shows a relative flat top to the arch when development advanced in one direction
Fig. 12.
Secondary ground support strategy.
Fig. 13.
Impact of blasting patterns/design on crosscut stability.
Fig. 14.
Studying the application of 3D LiDAR scanning technology.
Fig. 15.
Crosscut XC37 from 3 May 2018 LiDAR scan showing as much as 1.2 m of elevation change (red to green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)