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Improving ground control safety in deep vein mines

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ABSTRACT
Researchers with the National Institute for Occupational Safety and Health (NIOSH) in Spokane, WA, USA are conducting research in cooperation with the Hecla Mining Company at the Lucky Friday Mine in northern Idaho to improve ground control safety in deep vein mines. Because Hecla is mining at depths of more than a mile beneath the surface, the geology and ground stresses create unique requirements for mining and ground support. Special measures are being implemented by Hecla to limit the intensity of mining-induced seismic events and to avoid compromising the static and dynamic capacity of their ground support systems. NIOSH researchers are collaborating in these efforts by monitoring and assessing the fault slip mechanisms that initiate these seismic events and by quantifying the performance characteristics of the ground support systems.
KEYWORDS: rockburst; seismicity; dynamic ground support

1. INTRODUCTION

NIOSH researchers in Spokane, WA are conducting research in cooperation with the Hecla Mining Company at the Lucky Friday Mine in northern Idaho to develop improved methods for ground control safety in deep vein mines. Hecla is currently using underhand cut-and-fill mining methods to mine Ag-Pb-Zn ore from narrow, steeply dipping veins in the Gold Hunter deposit at a depth of over 7000 feet. Mining-induced stress increases near a large sill pillar in the mine's main production vein have created challenges for mining in these rockburst-prone ground conditions (Figure 1). As the sill pillar is being mined, its vertical extent decreases, which concentrates and progressively increases the stresses acting in the remaining portion of the pillar, thus increasing the potential for strain bursts. As mining progresses, local stresses are also being reoriented along the strike direction of problematic faults that intersect the sill pillar and dip 50° to 60° to the north. This compounds the rockburst issue by increasing the potential for fault-slip seismicity.

To reduce mining-induced seismic activity, the local stress field is being altered to reduce the magnitude of the stresses in the sill pillar and more favorably reorient the stresses acting along the faults. A nearby, sub-parallel, less-economic vein is being mined and backfilled to create a stress shadow that diverts the high horizontal stresses away from the mining horizon in the sill pillar and redistributes these stresses to more stiff, intact rock beyond the periphery of the mined shadow slot. The stress shadow also reduces the potential for fault-slip seismic events by reorienting and reducing the stresses that act along the orientation of these problematic faults.

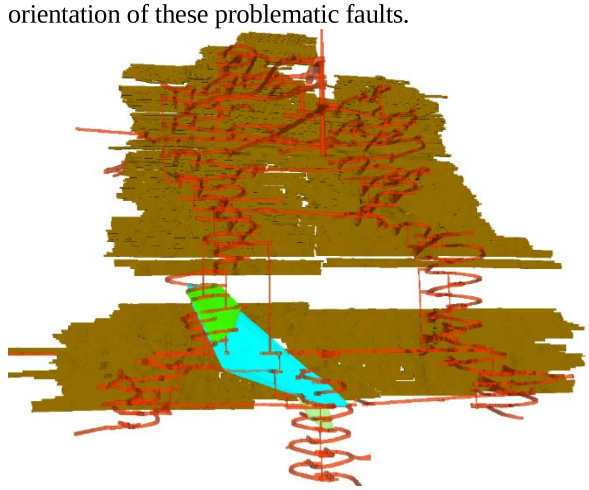

Figure 1: Schematic of development entries (red), backfilled stopes (brown), and faults (blue and green) in the Gold Hunter extension of the Lucky Friday Mine.

Current research activities include the use of seismic monitoring, photogrammetry, geotechnical instrumentation, 3D visualization, material property testing, ground support testing, and numeric modeling. This paper briefly discusses these research tasks and presents some of the technical innovations that have been developed.

2. SEISMIC EVENT MONITORING

NIOSH researchers are monitoring mining-induced seismic events at the Lucky Friday Mine using three seismic monitoring systems: Hecla's in-mine microseismic system, regional surface seismic stations,

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and a third monitoring system called the Intermountain Seismic Network (IMSN). The IMSN was developed and installed by NIOSH researchers to determine the source mechanisms of large mining-induced events (i.e., >1.5 magnitude). This system is currently comprised of eight close-in stations and one far-field station; however, it is being expanded to include additional far-field surface stations, as well as sensors installed underground at the mine. The far-field stations will be positioned distant enough from the anticipated seismic sources so that P and S wave arrivals will have sufficient separation to allow more detailed assessment of source mechanisms.

As shown in Figure 2, each IMSN surface station has a standard configuration consisting of an antenna/solar mast structure for the photovoltaic system, a vault for the battery/power distribution system, and another vault for telemetry/seismic equipment. The station's field-hardened, modular design not only protects the sensitive seismic equipment and electronics but also provides flexibility for installing different seismometers. Having a common configuration for each station simplifies the installation procedures, reduces troubleshooting time, and decreases the need for spare components. Personnel installing and maintaining the stations are able to quickly locate equipment, components, and power disconnects. The close-in stations are strong-motion stations with force-balanced triaxial accelerometers and seismometers, whereas the far-field stations use broadband triaxial seismometers. Seismic data is transmitted by radios or wireless cellular modems depending on site telemetry requirements.

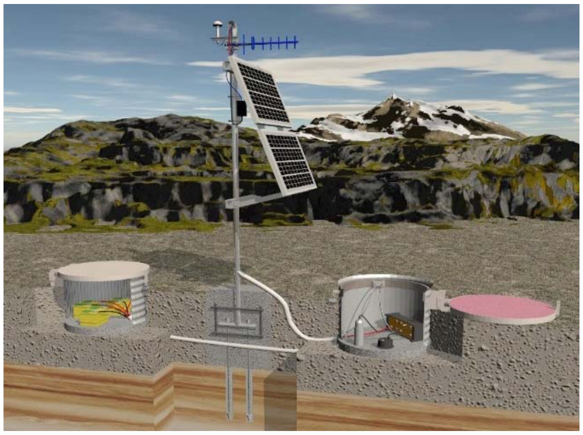

Figure 2: Typical configuration of an IMSN surface station for monitoring mining-induced seismic events.

Both the IMSN network and Hecla's microseismic monitoring system provide real-time waveforms of a seismic event that are in turn used to determine its location and magnitude. Because Hecla's in-mine sensors are located much closer to the active workings than the IMSN surface stations, their in-mine network can detect much smaller mining-induced seismic events. Furthermore, because their microseismic sensors are installed on different levels within the mine, their underground network also provides a much more accurate depth or elevation component for the location of an event. Focal mechanisms or moment tensors are calculated to determine the source of the event (e.g., slip on an existing fault or mining-induced rock mass fracturing). It is essential to identify the mechanism that caused the event in order to gain a better understanding of the ground conditions and also to develop appropriate methods for mitigating the effects of future events. The seismic moment, a measure of the energy released from an event, is also being determined and will be compared with numerical modeling results to gain additional insight.

3. PHOTOGRAMMETRY

Photogrammetry is a valuable tool for monitoring complex geometric changes on irregular surfaces. NIOSH researchers are using this technology in the laboratory to monitor large-scale tests with shotcrete support systems (see Section 7) and also at the Lucky Friday Mine to monitor bulk movement in underground entries and shear displacements along exposed fault planes. An explanation of the NIOSH photogrammetry system and further details concerning the software, hardware, methodology, field applications, and results are provided by Benton et al. (2014; 2015; 2016).

Quarterly photogrammetric surveys of exposed faults at the Lucky Friday Mine were initiated in January 2013 and are currently ongoing. The surveys are conducted at nine locations on seven different sublevels where two faults intersect the 54 ramp near the Gold Hunter orebody. As explained in Section 5, three-dimensional point cloud reconstructions of these sites are also used for mine visualization purposes. Using photogrammetric data from these sites, cross sections of the faults are compared over time to visualize and measure the geometric changes that have occurred. These cross sections may be developed at any location and at any orientation, thereby providing a comprehensive analysis of the movement at each site.

Photogrammetric measurement techniques are also being used to aid in the interpretation of displacement measurements from crackmeters that were installed by Hecla engineers to monitor fault movement. As shown in Figure 3, the vibrating-wire crackmeter measures displacement between two anchor points and thus, provides only a unidimensional measurement of the fault's movement (i.e., a displacement measurement along a single orientation). In contrast, the point cloud measurements obtained from photogrammetry provide a more complete three-dimensional characterization of the fault's movement and thus, help identify and quantify bulk ground movement, such as rib dilation, as opposed to actual movement along the fault. Using photogrammetry, a three-dimensional displacement vector can be calculated for an individual point or an entire vector field can be determined for a surface.

Figure 3: Crackmeter installed across an exposed fault in the wall of a ramp entry at the Lucky Friday Mine.

4. GEOTECHNICAL INSTRUMENTATION

Besides the crackmeters mentioned above, NIOSH researchers have also installed two sets of biaxial stressmeters (BSM's) to monitor stress changes in the host rock—five BSM's near the 5550-14 stope to measure stress changes during mining of the stress shadow stope and five BSM's near the 5550-11 stope to measure stress changes during production mining in the 30 vein. As noted by Seymour et al. (1999), the BSM is a rugged and reliable vibrating-wire instrument that is grouted in a drill hole to measure the magnitude and direction of the secondary principal stress changes in a plane perpendicular to the longitudinal axis of the instrument. Most of the stressmeters were installed in vertical drill holes to monitor changes in horizontal stress at vertical horizons near the sill pillar. Data from these instruments is being analyzed in conjunction with seismic monitoring data to determine the effect of mining advance and seismic events on stress distribution.

Figure 4: Single-acting closure meter and two earth pressure cells installed in the 5550-11W stope prior to backfilling.

Prior to backfilling, closure meters and earth pressure cells have been installed in the 5550-11 stope and the 6350-15 stope to monitor hanging wall-to-footwall closure and horizontal stress changes within the backfill as underhand cut-and-fill mining advances (Figure 4). Because of their robust design, the NIOSH closure meters have been able to provide stope closure measurements for over a year through more than five successive mining cuts beneath the location of the instruments (Figure 5). The geotechnical instruments are being monitored by underground data acquisition systems that are in turn connected to a computer server located on the surface, where the data is stored and displayed on a real-time basis.

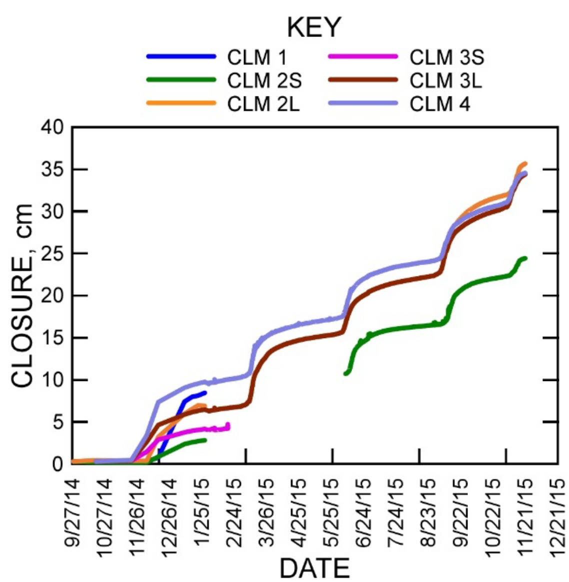

Figure 5: Horizontal closure measurements for the backfilled 5550-11 stope.

5. 3D VISUALIZATION

Complex spatial relationships between mining, seismicity, and problematic faults are being tracked by NIOSH researchers using a 3D visualization tool that was developed using the Unity® game engine (Unity

Technologies, 2015). As illustrated in Figure 6, this software tool integrates collected data and images by spatial location and time and thus helps the user interpret and analyze the complex interactions of diverse spatial and temporal data via a single, concise, interactive display (Orr et al., 2015). The 3D visualization contains a model of the mine workings, pertinent geologic structure, and quarterly photogrammetric surveys. Each of these components, as well as areas of active mining, can be stepped through time to observe changes. The visualization tool has two user modes. One mode allows the user to navigate around the rock mass and view stored data such as seismic events and instrument measurements. Another mode allows users to enter the mine workings and view data associated with specific workings, such as photogrammetric reconstructions (Figure 7). Future data may also include measured fault movements and the locations and characteristics of ground fall incidents.

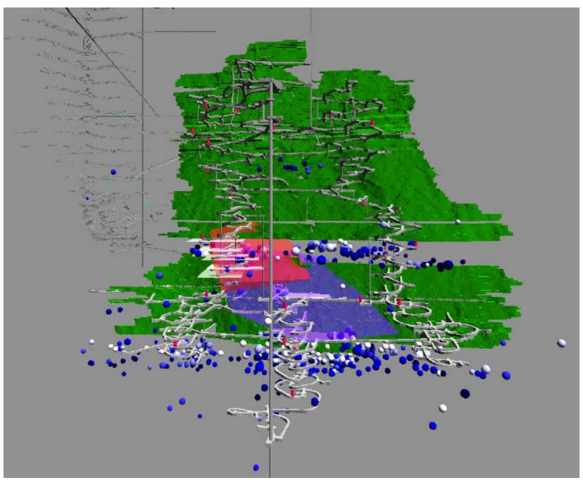

Figure 6: Unity visualization of Gold Hunter underground workings with problematic faults denoted in red and purple and seismic events represented by colored spheres.

Figure 7: Unity visualization showing a photogrammetry reconstruction of a ramp entry on the 5750 sublevel.

6. MATERIAL PROPERTIES TESTING

Drill core recovered from the BSM holes was logged and tested to characterize rock properties, improve the interpretation of stressmeter readings, and also provide inputs for numeric modeling. Standard tests were performed with representative samples from four different rock types, including unconfined compressive strength (UCS) tests, indirect tensile strength tests, and triaxial compressive strength tests. Because the Gold Hunter host rock is comprised of thinly bedded argillites, testing was performed both parallel and perpendicular to the bedding to determine anisotropic properties. Depending on rock type and bedding orientation, average UCS values ranged from 97 to 122 MPa, while average tensile strengths ranged from 4 to 11 MPa. Elastic properties were determined from UCS tests with strain-gauged samples. Young's modulus ranged from 41 to 90 GPa, and Poisson's ratio varied from 0.11 to 0.27. Triaxial compression tests were also conducted to determine Mohr-Coulomb strength properties (cohesion and friction angle).

Similar tests were performed to measure the strength and elastic properties of cemented paste backfill samples recovered from the mine (Johnson et al., 2015). These tests indicated that the tensile strength of the paste backfill ranged from about $^{1}/_{9}$ to $^{1}/_{12}$ of its compressive strength. Furthermore, UCS tests with strain-gauged samples provided a Young's modulus ranging from 2.28 to 3.59 GPa and a Poisson's ratio of 0.17 (Figure 8). Elastic properties for cemented paste backfill are difficult to measure and therefore, not widely reported in the literature.

Figure 8: Paste backfill sample equipped with strain gauges.

7. GROUND SUPPORT TESTING

The ability of ground support to withstand loading from a large seismic event depends in large part on its ability to maintain its support capacity while yielding and undergoing significant deformation. In deep mines, energy-absorbing rockbolts are often used in conjunction with surface support such as mesh and shotcrete to retain rockburst-prone ground. To quantify and evaluate the support strength and energy capacity of ground support systems utilizing shotcrete, NIOSH researchers designed and constructed a High-Energy High-Displacement (HEHD) test machine for conducting large-scale tests with reinforced shotcrete panels (Figure 9).

Figure 9: High-Energy High-Displacement test machine for conducting large-scale tests with reinforced shotcrete panels.

During a test, a large shotcrete panel is restrained by four rockbolts embedded in the concrete columns and then loaded from beneath by a spherical loading head attached to a hydraulic ram. The force and displacement applied by the ram (136 metric tons and 27 cm, respectively) are recorded during the test using an advanced data acquisition system. A more detailed explanation of the HEHD test machine is provided by Martin et al. (2015). Measuring the load-displacement characteristics of a full-scale shotcrete panel while it is restrained by rockbolts provides a more representative indication of the actual ground support provided by this material in an underground mine. As shown in Figure 10, the type of reinforcement embedded within the shotcrete has a major effect on the support capacity and behavior of the panel. As the force on the shotcrete panel increases, the shotcrete deforms and cracks, allowing the tensile loads in the panel to be redistributed to the more ductile fibers or mesh.

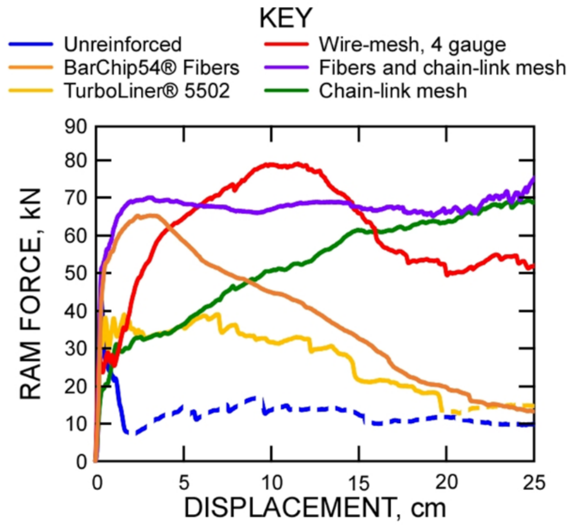

Figure 10: Force versus displacement graph for shotcrete panels with different types of reinforcement.

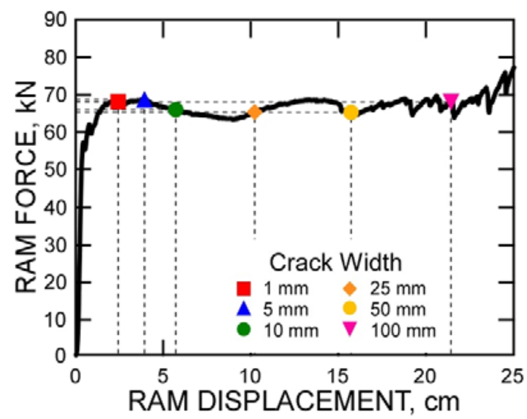

Figure 11: Force, displacement, and crack width opening for a shotcrete panel reinforced with chain-link mesh and 54-mm-long macro synthetic fibers at a 6.5-kg/m^3 dosage.

Photogrammetry is used during the HEHD tests to measure the volumetric deformation of the panel and the opening width of cracks that are developed within the shotcrete. The force and energy applied to the panel are referenced to these photogrammetric measurements as shown in Figure 11. Using this information, the panel tests results are then compared with field observations in underground mines to estimate the remaining support capacity of the applied shotcrete based on photogrammetric volume calculations or visual observation of crack widths (Raffaldi et al., 2016a).

8. NUMERICAL MODELING

Map3D™ (http://www.map3d.com), a boundary element software program, is being used to evaluate mining-induced stress changes and fault stability in response to sill pillar mining (Figure 12). As expected, stresses in the sill pillar increase as the vertical extent of the pillar decreases. As mining advances, these stress increases result in an increased potential for strain bursts in the pillar accompanied by a relaxation of the normal forces acting on the faults, which in turn lead to an increased potential for fault-slip seismicity. In the model, horizontal closure of the backfill stopes is roughly calibrated to actual in-mine measurements.

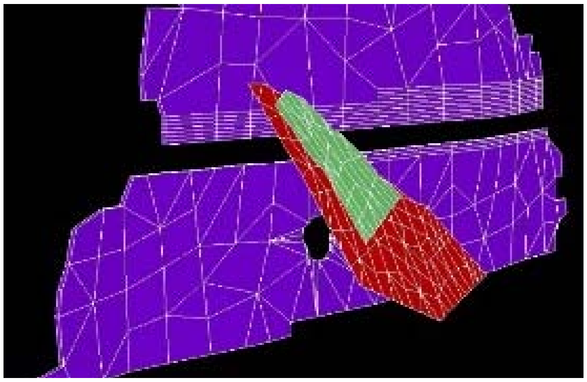

Figure 12: Map3D model geometry showing backfilled stopes (purple), faults (green and red), and remaining sill pillar and host rock (black).

The finite difference code, FLAC3D™ (http://www.itascag.com/software/flac3d), is being used to model the Gold Hunter sill pillar. Host rock and backfill properties are based on the in situ measurements and laboratory testing described earlier in this paper. FLAC3D™ allows for a detailed extraction sequence to be simulated in which the orebody is sequentially mined and backfilled. The model has been used to back-calculate the rockmass deformation modulus and cohesive strength in the vicinity of the Gold Hunter sill pillar.

The discrete element code, UDEC™ (http://www.itascag.com/software/udec), is being used to perform fully dynamic simulations of rock fracture and ejection caused by seismic loading. A synthetic rock mass was modeled consisting of a series of discrete blocks that can fracture and shear or fully detach from the model in response to loading (Raffaldi and Loken, 2016b). This has been incorporated into a model of a typical mine drift and is being used to investigate energy transfer between the ejected rock and the reinforcement and surface support components of the ground support system (Raffaldi and Loken, 2016c).

9. CONCLUSIONS

Research is being conducted by NIOSH in collaboration with the Hecla Mining Company at the Lucky Friday Mine to develop improved technologies for ground control safety in deep vein mines. To gain a better understanding of mining-induced seismic events and fault-slip seismicity, a network of surface seismic stations near the mine site are being monitored on a real-time basis along with geotechnical instruments installed underground in the host rock, backfill, and at fault locations. To provide further insight, photogrammetry surveys are periodically being conducted to monitor bulk movement in underground entries and to measure shear displacement along exposed faults. Much of this information is being incorporated in 3D visualization software to help synthesize and interpret the data in terms of the mine's infrastructure, production stopes, and geology. Laboratory tests are being performed to measure the material properties of the mine's host rock, shotcrete, and cemented paste backfill. Large-scale tests are being conducted to determine the ground support characteristics of reinforced shotcrete systems. Finally, several different types of numeric models are being used gain a better understanding of the geomechanical behavior of the host rock and backfill, particularly in regard to seismic loading. Advances in these research areas will hopefully lead to improved ground support and mine design practices for deep underground mines.

10. ACKNOWLEDGEMENTS

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