

## Investigation of Acoustic Emission Sensors for Ground Control Hazard Recognition in Underground Mines

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### ABSTRACT

Mine-wide ground control stability is essential to any mining operation to prevent catastrophic failure of underground structures. The ability to recognize or indicate the potential for ground control hazards in underground mine operations is highly desirable to reduce or eliminate ground-control-related injuries and fatalities. The acoustic emissions (AE) form of non-destructive testing has been used for decades to determine material or machine deterioration or potential failure. This paper presents the findings of research in AE with the results of laboratory bolt pull tests and comparisons to field experimentation, including AE sensors and bolt load data in an underground stone mine. The goal of the project is to compare laboratory results of AE sensors on roof bolt pull tests with field experimentation to determine the capability of predicting bolt failure or roof deterioration.

### INTRODUCTION

Mine-wide ground control stability is essential to any mining operation to prevent catastrophic failure of underground structures. The ability to recognize or indicate the potential for ground control hazards in underground mining operations is highly desirable to reduce or eliminate ground-control-related injuries and fatalities. Typical ground control monitoring devices involve drilling into roof or rib, grouting or gluing of sensors, and dedicated cabling for data collection. One of the original goals of this research was to develop a methodology for a simple wireless device that could provide an indication or warning of potential roof bolt or roof failure. Various types of nondestructive testing (NDT) have been used for decades to determine material or machine deterioration or the potential failure of either. One type of NDT is acoustic emission (AE) monitoring, which has been studied for use in mining to predict rock bursts and mine failures since the 1940s (Obert, 1941; Obert and Duvall, 1942). The primary goal of the work was to compare laboratory results of AE sensors on roof bolt pull tests with field experimentation to determine the capability of evaluating bolt loading or roof deterioration in an underground stone mine. Bolt pull tests were conducted in the laboratory to establish a repeatable trend of AE activity versus bolt load. The second part of the project was to then install bolt load cells in an underground stone mine and monitor AE activity in the vicinity of mining.

### BACKGROUND

AE is defined as a transient elastic wave generated by the rapid release of energy within a material (Lockner, 1993). When a

structure is subjected to an external stimulus (change in pressure, load, or temperature), localized sources trigger the release of energy in the form of stress waves, which propagate to the surface and are recorded by sensors. Sources of AE vary from natural events, like earthquakes and rockbursts, to the initiation and growth of cracks, slip, and dislocation movements, melting, twinning, and phase transformations in metals (NDT Resource Center, 2018). For the application in this study, we are interested in the AE events generated by the load and stress in the roof bolt shaft, along with the localized fracturing and cracks generated around the roof bolt installations.

AE testing has become a recognized NDT method commonly used to detect and locate imperfections in mechanically loaded structures and components (Hallier, 2003). AE tests are often performed on structures while in operation (i.e., mining extraction and roof loading) because this provides adequate loading for propagating defects and triggering AEs. AEs always originate with stress of the material or mechanism. Depending on the magnitude of the stress and the properties of the material, an object may return to its original dimensions or be permanently deformed after the stress is removed. The most detectible AE takes place when a loaded material undergoes plastic deformation or when a material is loaded at or near its yield stress. The amount of energy released by an AE and the amplitude of the waveform are related to the magnitude and velocity of the source event. The amplitude of the emission is proportional to the velocity of crack propagation and the amount of surface area created. Large, discrete crack jumps will produce larger AE signals than cracks that propagate slowly over the same distance (NDT Resource Center, 2018).

The intent of this research is to show that AE sensors attached to roof bolts can be used to show the increased level of bolt loading or surrounding rock stress and deformation. The experiment is set up to compare roof bolt stress and deformation from laboratory loading and pull test with field instrumentation at an underground stone mine using AE sensors. The AE sensors pick up the energy generated from stress and deformation both during loading and while the material is in a steady or constant stress condition.

Previous experiments with AEs have focused mostly on laboratory studies for rock fracturing (Anderson and Ruzzi, 1987). For underground mine applications, a study was conducted with an AE sensor attached to a roof bolt in a western Pennsylvania longwall

mining operation (Meiksin, 2010). The sensor was installed at the longwall headgate and monitored for one 8-hour shift, showing increased levels of AE activity as the longwall approached.

### ACOUSTIC EMISSION EQUIPMENT

The AE sensor provides the essential interface between the mechanical waves generated by the structure or material to the converted electrical pulses that provide the signal. This conversion is at the heart of AE monitoring and has enabled the ability to have several sensor types. The most common types are geophones, hydrophones, accelerometers, and AE transducers. For most AE work, one of the latter three types is generally used, each being more significantly sensitive than geophones. These sensors usually consist of a polycrystalline ceramic element polarized to exhibit piezoelectric behavior. Depending on its construction (shape, coupling, damping, housing, etc.), each sensor has a resonant frequency level at which it is most responsive and below which its response is often quite uniform.

Piezoelectric discs are normally used in AE sensors to pick up the stress wave and translate the energy into a voltage, which is then transmitted. The choice of resonant frequency for the AE sensor is determined on the basis of the type of material being monitored. For steel structures or roof bolts, 150-kHz resonant frequency sensors are most often used. Concrete or rock structures use a lower resonant frequency, such as 30 kHz, in order to pick up the slower moving stress waves.

A 150-kHz resonant frequency sensor was attached to roof bolt plates during both the laboratory bolt pull test and in-mine bolt load cell instrumentation to capture the AE activity associated with the bolt steel material. A 30-kHz sensor is used in the field along with the 150-kHz sensors in an attempt to capture rock fracture in the area around the installed bolt with both attached to the roof bolt plate. Magnets were attached to the sensor casing at the detection end with high-strength glue and then placed on the bolt plate along with ultrasonic gel to improve conduction and eliminate air gaps produced by nonconformities in the steel material.

When the roof bolt is loaded and the steel takes on a stress level, the material changes, creating AEs; this is referred to as an AE event. AE detection is the recognition of the presence of a signal, which is typically accomplished by the signal crossing a detection threshold. The threshold for the sensors used is 45 decibels (dB). An AE hit is the detection and measurement of an AE signal on a channel. Typically, one sensor is connected to one channel on the data collection device.

The data acquisition system used for both the laboratory pull tests and the roof bolt monitoring field test was the Mistras Sensor Highway III structural monitoring system, configured for 24 channels (Mistras Group, 2014). This data acquisition system includes an onboard microprocessor with Windows operating system and the AEWin software designed to process AE signals and display results in various graphical formats (Mistras Group, 2014). For both the laboratory and field tests in this research, the primary AE parameters were set up to monitor hits and associated amplitude received by the sensors during each AE event.

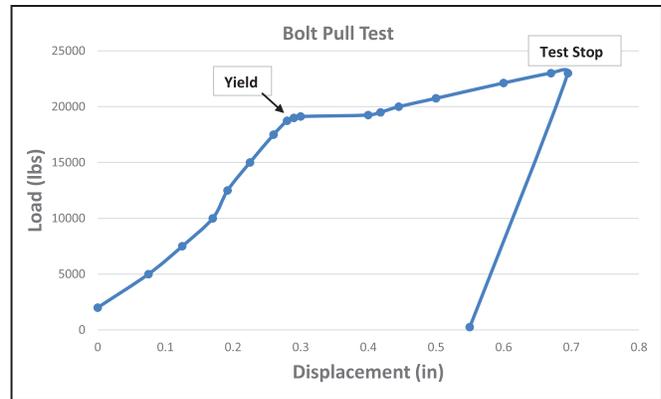


Figure 1. Typical graph of the load versus displacement of the bolt during the pull test.

### LABORATORY TEST

Bolt pull tests were conducted using a Tinius Olsen testing machine at the Pittsburgh Mining Research Division laboratory (Tinius Olsen, 2018). The machine program was set up to pull bolts past yield and to failure, using various load scenarios while measuring load and displacement with the Tinius Olsen machine and AE activity with the Mistras data acquisition system. Two 150-KHz sensors from Physical Acoustics Corporation were placed on the bolt plate with magnets as described in the preceding section.

The bolt specifications were a 1.2 m (4 ft) rebar at 1.59-cm (5/8-inch)-diameter and Grade 60 steel. The bolt plate was a 1/4-inch dome plate. Bolts were typically installed in the machine with approximately 18-inch gage length or an 18-inch space between two crosshead clamps for the bolt pull zone. Load test scenarios included steady displacement at 0.25 cm (0.10 inch) per minute, along with 1-minute holds at various loads, including 5,000- and 10,000-pound levels. All bolts were pulled to yield at approximately 19,000 pounds and then to failure or ultimate strength. Figure 1 shows a typical load versus displacement curve during the bolt pull test. Several tests were conducted with consistent repeatability of load versus displacement for the bolt yielding and load versus hits for the AE activity.

When the bolt is loaded and begins to take on stress, AE events will begin and increase in number with the level of stress. These events are then measured by the number of events, which exceed a predetermined threshold and constitute an AE hit. The AE hit is then recorded by the monitoring system software, creating a curve, which increases with the bolt loading or stress as shown in Figure 2.

### FIELD INSTRUMENTATION AND TEST SITE

The field test is ongoing at the Pleasant Gap Mine, an underground room-and-pillar limestone mine owned by Graymont (Pleasant Gap, PA) and located in central Pennsylvania. A map of the Pleasant Gap Mine is shown in Figure 3. The limestone seam dips approximately 18 degrees in the southeast direction. The mine is located within a structurally complex area of tightly folded anticlines and synclines. The study area for both the microseismic and AE tests, highlighted in Figure 3, is within one of the deepest parts of the mine, approaching 425 m (1,400 ft) in overburden.

The Pleasant Gap Mine operates in the Valentine Formation, which is typically light gray, extremely fine-grained limestone, approximately 21.3 m (70 ft) thick. The overlying Centre Hall Formation contains approximately 9.1 m (30 ft) of medium-dark gray limestone (after Murphy et al., 2018). During mine development, the roof horizon begins at the parting between the Valentine and Centre Hall Formations. Within the overlying Centre Hall Formation, horizontal bentonite clay bands are particularly significant because they can be conduits of water and extend great distances (Rones, 1969). Below the Valentine Formation is the Valley View Limestone member of the Linden Hall Formation. It is typically dark-gray and averages 12.8 m (42 ft) thick.

Two prominent fracture patterns, referred to as the J1 and J2 joints by the operator, are found throughout the mine. J1 joints are generally parallel to the direction of maximum horizontal stress and are roughly parallel to the strike of the strata. J2 joints are nearly perpendicular to the direction of maximum horizontal stress. J1 joints are sometimes open, especially at shallow overburden. Both

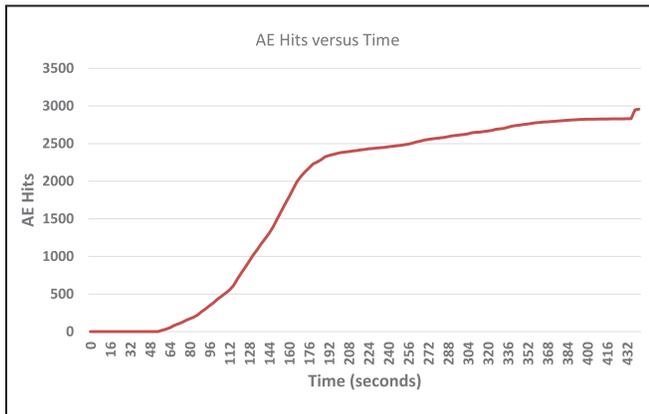


Figure 2. Typical graph of the AE activity (hits vs. time) during the pull test.

J1 and J2 joints are often calcite filled. The occurrences of joints are irregular throughout the mine but have been observed in the area currently being studied. Bedding planes were easily identified due to small bentonite clay bands within the strata. In isolated locations, the bentonite clay bands and blasting damage caused areas of sloughing that had to be navigated carefully.

The J1 and J2 joints were identified near the mining faces in development entries 31E, 30E, and 29E. Cutters are present within the study area and oriented along the mine entries but tended to break along the J1 joints. Roof damage was increased when J1 and J2 joints intersected, creating a pot-out of 0.9 to 1.2 m (3 to 4 ft) high and exposing the weaker Center Hall Formation in the roof.

Two 3.4-m- (11 ft)-mechanical bolts at 7/8-in diameter and Grade 75 steel were installed along with Geokon Model 3000-100 (100 kip capacity) load cells and 7.6-cm- (3 inch)-square by 5.1-cm- (2 inch)-thick, solid-steel washers to stabilize the load cell during loading (Geokon, 2018). One 150-KHz and one 30-KHz AE sensor were installed to each of the bolt installations. Bolts were installed manually with a battery-operated hand drill to a maximum torque of 50 ft-lb. This was the limit of the drill. Although the bolts were specified to be torqued to 250 ft-lb, it was determined that the anchors would likely not slip and a relative load could be monitored for comparison to the AE activity. The bolts were installed in the crosscut area of 31E x 37S, indicated by the triangles shown in Figure 4.

AE sensors were then attached to the roof bolt plates with magnets to capture the AE events in the roof strata via the point anchored mechanical bolt. A 150-KHz and 30-KHz sensor was attached to each roof bolt plate for measuring the AE events in the bolt and in the surrounding strata, respectively. Figure 5 shows a photo of the load cell and AE sensor installation. Each sensor has a dedicated coaxial cable attached and routed back to the data acquisition system approximately 250 feet away. Figure 6 shows a photo of the dedicated data acquisition system for the AE sensors (large box)

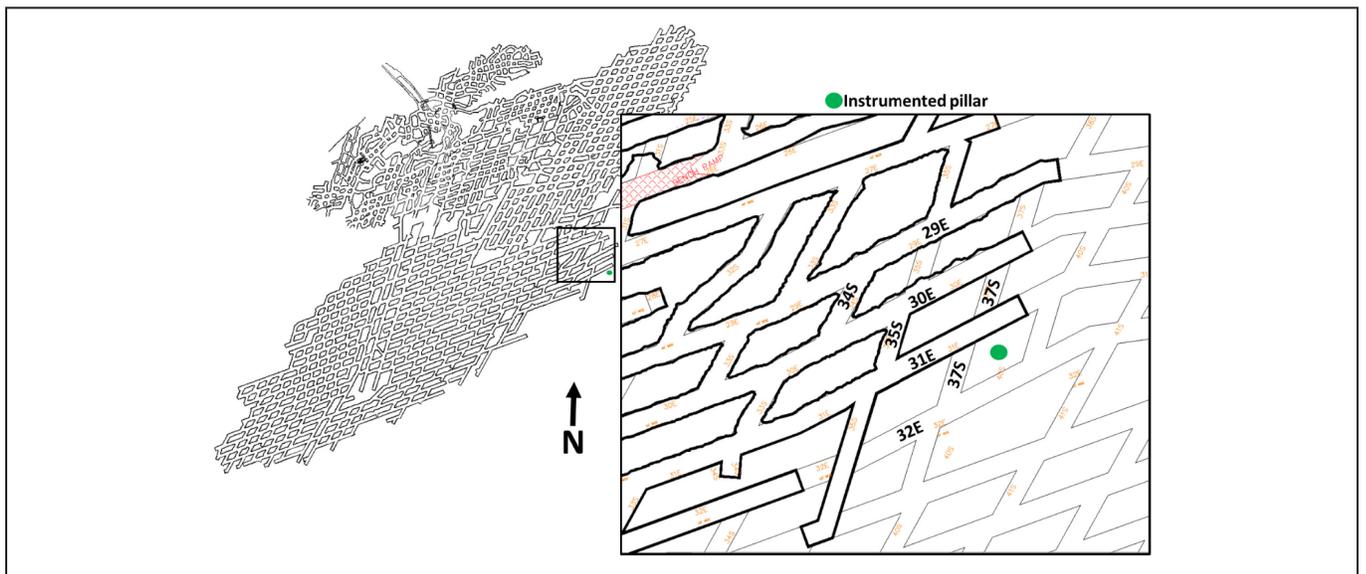


Figure 3. Map of the Pleasant Gap Mine, including a detailed view of the instrumented area for the field test (after Murphy et al., 2018).

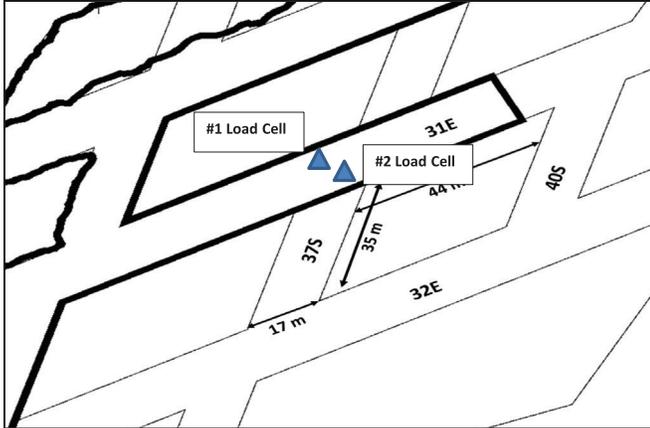


Figure 4. Location of bolts with instrumentation at the Graymont Mine.



Figure 5. Load cell and AE sensor installation.



Figure 6. Mistras Sensor Highway III data acquisition system (large box) and the MIDAS unit for bolt load cells (small box).



Figure 7. Area of Graymont mine where the instrumented bolts were installed (after Murphy et al., 2018).

and the MIDAS unit for the bolt load cells (small box). Figure 7 shows a photo of the area where the bolts were installed.

#### DATA ANALYSIS

The field testing began in August 2017, along with another field experiment using microseismic technology at the same location in the Graymont mine. The two projects were coordinated with the intent of possible overlapping data sets and potential correlations. The first six months of data collection were essentially a period of trial-and-error testing of sensors and collecting data. After establishing which sensors to use, it was also determined that bolt load cells would be necessary in order to show that the AE data was representative of bolt load or roof conditions and not of all the associated mine noise with the mining activity. The load cells and AE sensors were then installed in January 2018, and initial data results are shown in Figure 8. The primary y-axis is the bolt loading in pounds, and the secondary y-axis is AE hits. The gradual load increase on the bolts over the first 5 weeks is also represented in the increase in AE hits from the sensors. A significant amount of AE activity was seen on February 20th; however, it was determined that roof bolting activity in the nearby crosscut was the primary reason for this dramatic increase in roof noise.

An area of interest and hypothesis is if an increase in bolt load and simultaneous increase in AE activity for the 150-KHz sensor is either preceded or followed by an increase in the AE activity of the 30-KHz sensors. This would indicate roof cracking or deterioration, causing the increase in bolt load. However, with point anchor bolts, such as those installed for this test, there could be lateral roof movement and no change to the loading on the bolts. The roof cracking would then occur with little or no bolt loading. This would also be expected in a mine experiencing cutter roof development and little roof sag, such as this mine. The data thus far does indicate a greater amount of AE hits for the 30-KHz sensor versus the 150Hz sensor, with the increased activity at the center of the graph in Figure 8 coinciding with only a slight increase in bolt load and no extraneous mine activity occurring. This is preliminary data and will be further monitored with additional field testing data.

AE theory states that emission amplitude is proportional to the crack velocity (Hallier, 2003). A sudden discrete, crack event will produce a greater signal than a slow-moving event over the same distance. Figure 9 shows a diagram of the AE hits with the associated hit amplitude. The blue bars are the 30-KHz sensor, and the red bars are the 150-KHz sensor for both bolts. There

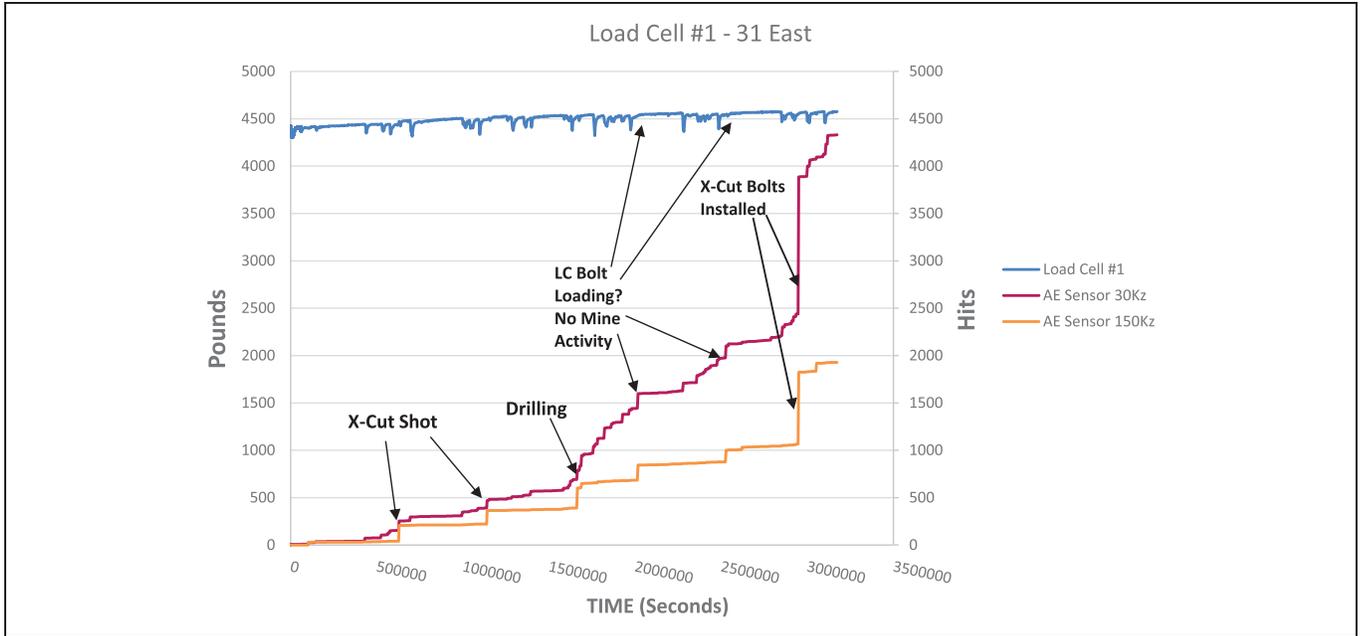


Figure 8. Load cell #1 with bolt load and AE hits.

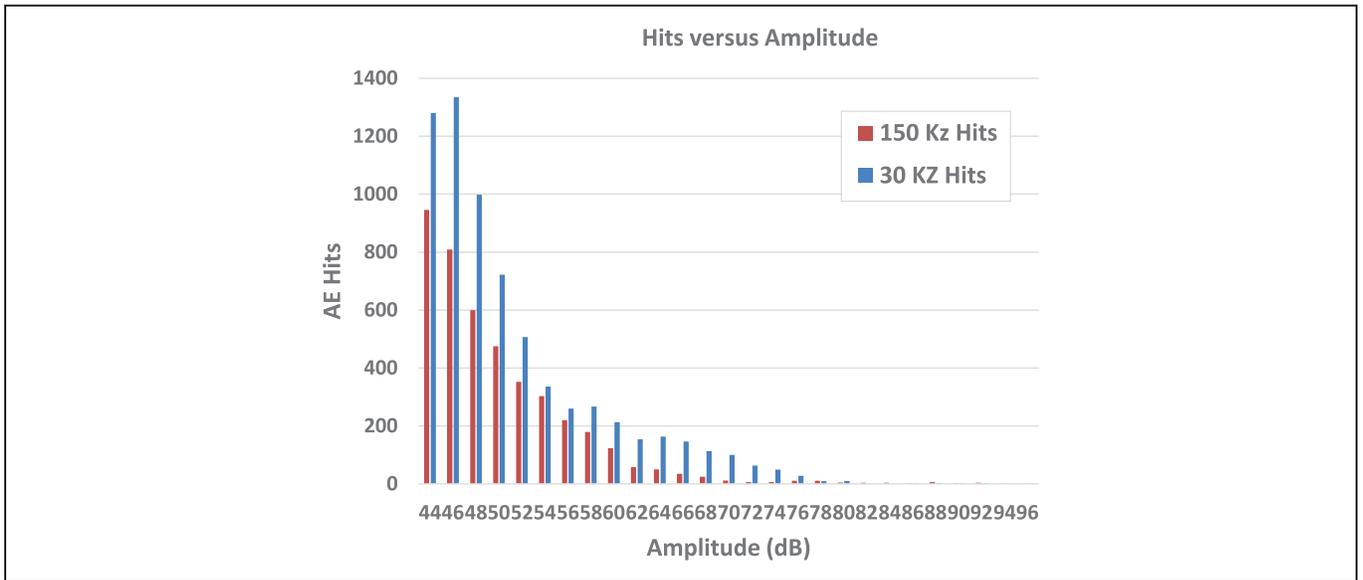


Figure 9. AE hits with amplitude for the 30-KHz sensor and 150-KHz sensors.

is additional activity at all amplitudes from the 30 KHz sensor, representing the more sensitive lower frequency. The 150 KHz sensor shows amplitude readings more predominantly in the 44 to 60 decibel range, which is typical of metal materials. The hypothesis is that the 30 KHz sensors will pick up the higher amplitude readings from “more significant” cracks in the roof rock; however, at this point in the study, further data analysis is necessary to distinguish between mine activities and roof rock deterioration.

**CONCLUSIONS**

Stakeholder interactions with NIOSH researchers have indicated that monitoring for hazardous ground control conditions is very

desirable. The project has thus far provided some indication that the potential exists for small and easily installed devices to monitor and predict changing ground conditions. For the current study, a monitoring system has been installed in an underground limestone mine in central Pennsylvania. The study will document bolt-loading response and associated AE activity as mining activity continues for developing a pillar in the instrumentation area. Bolt loading and AE activity will be continuously monitored with the bolt load cell and AE sensors. Thus far, the field experiment has shown that the AE sensors will pick up noise in the surrounding rock of the attached roof bolts. However, the majority of this noise has been mining activities, such as drilling, shooting, roof bolting, and scaling.

There is some indication that the AE activity is separate from the mine activities; however, without any sign of increased load in the roof bolts, it is difficult to distinguish the source. This lack of distinguishing characteristics for increased bolt load or deteriorating roof rock has been compounded by the fact that the bolts were installed post-mining cycle, and the intersection has been relatively quiet up to this point.

There is some indication in the field data that, as bolt load increases, the AE events increase concurrently. This matches with what was experienced during laboratory bolt pull tests. The goal is to develop a greater understanding for the potential of detecting changing load and roof conditions with the use of AE sensors mounted to roof bolts.

#### DISCLAIMER

The findings and conclusions in this report are those of the author and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by NIOSH.

#### REFERENCES

- Anderson, S.J. and Ruzzi, P.L. (1987). *Acoustic Emission Monitoring of Fracture Development*. Report of Investigations, RI-9077. U.S. Department of the Interior, Bureau of Mines, pp. 15.
- Geokon. (2018). *Load Cells (Electrical Resistance) Model 3000*. Lebanon, NH: Geokon, Incorporated.
- Hallier, C.J. (2003). *Handbook of Nondestructive Evaluation*. 1st ed. "Chapter 10: Acoustic emission testing." Columbus, OH: McGraw-Hill Professional.
- Lockner, D. (1993). "The role of acoustic emission in the study of rock fracture." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 30(7): 883–899.
- Meiksin, Z.H. (2010). *Technology for the Early Detection and Warning of Impending Underground Mine Roof Fall*. Final Report for Small Business Innovation Research (SBIR) under grant 1R44OH009679.
- Mistras Group. (2014). *Sensor Highway III*. Princeton Junction, NJ: Mistras Group, Inc.
- Murphy, M.M., et al. (2018). "Development of a comprehensive pillar and roof monitoring system at a steeply dipping underground limestone mine." In: Proceedings of the SME Annual Meeting. Minneapolis, MN: Society of Mining, Metallurgy & Exploration, preprint 18–018.
- NDT Resource Center. (2018). *Introduction to Acoustic Emission Testing*. Alexandria, VA: National Science Foundation, Non-Destructive Testing Resource Center.
- Obert, L. (1941). *Use of Subaudible Noise for Prediction of Rock Bursts*. Report of Investigations, RI-3555. U.S. Department of the Interior, Bureau of Mines.
- Obert, L. and Duvall, W. (1942). *Use of Subaudible Noise for Prediction of Rock Bursts: Part II*. Report of Investigations, RI-3654. U.S. Department of the Interior, Bureau of Mines.
- Rones, M. (1969). *A Lithostratigraphic, Petrographic and Chemical Investigation of the Lower Middle Ordovician Carbonate Rocks in Central Pennsylvania*. General Geology Report G 53. Pittsburgh, PA: Bureau of Topographic and Geologic Society, pp. 224.
- Tinius Olsen. (2018). *Products: Tension & Compression*. Horsham, PA: Tinius Olsen TMC-United States.