Ground Control and Geologic Assessment in Mining
Through the Use of Geophysical Tomographic Imaging

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Abstract: Identification of adverse ground control conditions and geologic anomalies during underground excavation using modern mechanized mining systems is a major challenge facing the mining industry. Often, unexpected geologic anomalies that affect rock mass quality are encountered more rapidly, leaving the mine operator with insufficient time or information to deal with the changing ground conditions.

The Rock3D™ geophysical mapping system developed by NSA Engineering, Inc., offers substantial benefits over the conventional geologic/stress-detection methods and has been successfully applied to coal and hard-rock mines for mapping...

- 3-D stress distribution for identification of ground hazards;
- Geologic structures ahead of longwall mining and within a specific stope area or across several stopes;
- Stope shape after blasting;
- Extent of failure zone surrounding a sink hole;
- Underground cavities.

One of the most significant benefits offered by the Rock3D™ system is that tomographic images can be produced in near-real time, providing mine operators with information on how to deal with potential hazards on a day-to-day basis.

This paper focuses on the application of Rock3D™ technology for delineating hazards caused by stress and geologic anomalies. Several case histories from coal and hard-rock mines are summarized. For example, (1) in a German bump-prone coal mine the yield drilling method was used to verify the effectiveness of the Rock3D™ system in detecting stress anomalies ahead of longwall mining; (2) in an Australian longwall mine, the periodic shield loading was determined; (3) in an Australian nickel mine, the periphery of a collapsed zone “sinkhole” that may present a future risk was delineated, and (4) in a gold mine in the United States, cavities having dimensions that varied from several meters to several hundred meters were mapped.

Key Words: geophysical, tomographic imaging, ground control, geologic assessment, longwall ground hazard
Introduction

Coal and metal/nonmetal production is projected to increase because of growing demands. Challenges in new technologies that enable mine management to characterize geotechnical conditions and responses to mining rates are therefore essential. Rock failures due to stress and geological anomalies are an ever-present hazard in the underground mining environment. The consequences from such failures can range from production delays to equipment losses, and in the worst case, the loss of human lives. Conventional hazard detection and mitigation technologies have failed to fully address both personnel safety requirements and high production demands of today’s mining. Advances in computer technologies and data processing allowed geophysical techniques to become more popular for identifying potential hazards ahead of a mining face.

NSA Engineering, Inc., has developed and applied seismic tomography imaging techniques in various applications to provide a clear view of what lies ahead. This technique is similar to the technology used in the medical field to produce CAT (Computer-Aided Tomography) scans. The principle behind Rock3D™ is that seismic energy travels through different material types with different attenuation and velocity levels. Seismic waves will travel faster through competent or highly stressed rock than through broken rock or voids.

Advantages of the Rock3D™ system include time savings in that it is easy to install and operate, requires minimal training, and data are easily interpreted. A second advantage is the relatively low cost of all the components. The system is the only tomographic system available that utilizes mining equipment such as the shearer in coal mines as the seismic source. This allows continuous operation of the longwall while tomograms are being generated. Tomographic images are presented in a format that includes the actual mine plan and prior identified structural features and are usually produced within minutes of completion of a shearer pass. The output can also be combined with other available rock mechanics data to better understand any trends that may cause ground control problems. Such capabilities within the system software provide proactive information that can potentially reduce downtime and significantly improve mine safety.

In general, Rock3D™ provides near-real-time graphical representations of (1) relative stress concentrations as they migrate across an underground rock mass, (2) structural discontinuities, such as faults, joints, or shear zones, and (3) geological anomalies such as sand channels or rolls, in coal mines.

The objective of this manuscript is to describe the Rock3D™ system and present results from field studies in coal and hard-rock mines where the Rock3D™ system was used successfully. Also described are the basics for this technology and additional applications where this technology can be applied to a variety of short- and long-term monitoring studies.
The Rock3D™ System

The Rock3D™ system consists of commercially available hardware and proprietary software. The system hardware is simple and is designed to measure vibration either by the shearer cutterhead during coal mining, by development/stope blasting in hard-rock mines, or by other types of seismic sources. In general, the hardware is comprised of an intrinsic safety barrier (for gassy mine applications), geophones that are attached to roof bolts in entries, and cables that carry the signal to a seismic data acquisition system as shown in figure 1. The entire system is located in the mine, and the data can be easily transferred to the surface or any mine office through modems.

The Rock3D™ system incorporates highly sophisticated tomographic software code for reconstructing color-coded images given a set of observations of energy passing through a medium. The path followed by the seismic wave from a source to a receiver is represented as velocity and attenuation rays. Velocity tomography is based on the time it takes for each ray to travel through rock from the source to the receiver. Attenuation tomography is based on the reduction in the power of the seismic signal as it travels from the source to the sensors.

Velocity tomography generates a velocity map from signal travel-time data. Usually the source and receiver locations and a corresponding travel time are recorded for each ray. The actual refracted ray path and velocity variations along the ray path within the medium are unknown. A forward velocity model is constructed to estimate travel time and the refraction path for each ray. This is accomplished by approximating the velocity medium as a continuous grid mesh.

Travel times are estimated by propagating a finite-difference wavefront across the mesh from a known source location. For low-velocity contrasts, straight rays are often assumed. In higher velocity contrasts, rays will bend (refract), resulting in lower arrival estimates and ray coverage as illustrated in figure 2.
Figure 2. A grid of velocity values for comparison of straight rays versus curved rays.

As the seismic signals travel through rock, geological anomalies or highly stressed/fractured zones ahead of mining absorb the vibrations, attenuate the signal, and produce variation in the measured magnitude of the seismic signals at the sensors. Attenuation tomograms are generated and are related to fracturing and stress under the assumption that an area of higher stress results in microfracture closure and, thus, lower attenuation levels. The mining engineer can use the information from these tomograms to observe stress behavior and ground conditions ahead of mining.

**Rock3D™ Field Applications**

The Rock3D™ system has been tested successfully and installed at many mines worldwide, for various applications, with new installations forthcoming at underground hard-rock and coal operations in the near future. In addition, numerous mining, civil construction, and archeological projects are planning to utilize this technology to readily map ahead of the TBM and to evaluate foundation stability. The Rock3D™ technology has been used in mines in the United States, Australia, Germany, Ireland, South Africa, Poland, and Canada for stress and geological mapping, ore deposit delineation, solution cavity location, water migration pathways identification, characterization of ground conditions within tunnel alignment, and archeological mapping. The following are recent Rock3D™ applications in both coal and hard-rock mines:

**Recent Rock3D™ applications for coal mining:**

At a deep longwall mine in Germany, where high stress zones on the face are known to contribute to severe ground control problems such as face bumps, Rock3D™ was utilized to detect stress concentration zones and to delineate bump-prone areas. The longwall panel utilizing the single-entry system was at an average depth of 1,130 m, and 323 m wide. Mining height at the face was approximately 2 m. The panel was located between two major fault zones, and several minor faults cut the panel, with displacements up to 4.3 m.

High stress conditions present on the face are due to one or a combination of factors, such as (1) high depth of cover, (2) presence of geological structures, (3) mining of a seam 170 m above, (4) massive 20-m-thick sandstone above the seam, (5) high-strength gob-sealing walls built along the tailgate entry, affecting caving of the gob, and (6) panel orientation with respect to the fracture zone in the roof.
The system was installed to determine if tomographic images produced on a daily basis could be used to identify zones of high stress concentrations on the longwall face. Sixteen geophones were installed, with eight in the headgate and eight in the tailgate. The geophones were attached to angled roof bolts at 15- to 20-m spacings, with the closest geophones 10 to 15 m ahead of the face. The data were transmitted through a modem to the surface so that the mine could remotely monitor and analyze data on the surface quickly and cost-effectively.

Data files were collected and evaluated by calculating the power spectrum between 70 and 150 hertz, which was the frequency band that contained most of the shearer signals. From this, data filtering was set up to produce the most accurate signal attenuation tomograms. The noise vibration signal produced by the shearer appeared to be transmitted clearly in the rock mass.

![Figure 3. Fault and forward abutment mapping ahead of mining – Germany.](image)

The tomograms produced over a period of five days showed lower stress zones extending from the middle of the face toward the tailgate, as shown in figure 3. The fault present at the tailgate (left) side of the face diverts the velocities. This fault does not appear to build strain energy. The fault at shield 50 (right-hand side) had a major effect on how the seismic rays traveled. This fault appeared to contain highly fractured rock to within 25 m ahead of the face. The fractured zone continued to move ahead of the face, and a high-stress zone developed 50 m ahead of the face between shields 1 and 48. The fault, in combination with the overlying massive sandstone, contributes to a high stress concentration between shield 50 and 120. This zone disappears when the roof member caves. The tomograms indicate that the forward abutment extends to 20 m ahead of the face, with the exception of the tailgate and headgate corners.

The mine used the drilling-yield method to verify the accuracy of the tomographic images. Figure 4 compares the results using the drilling-yield and Rock3D™ data. The figure shows a correlation between high stress areas identified by the Rock3D™ method and those identified by the drilling-yield method. Other comparisons gave a similar high level of correlation. The results indicated that Rock3D™ could become a viable tool to replace the yield-drilling method, with consequent gains in cost-efficiency and productivity.
Rock3D™ was deployed in an attempt to delineate the extent of the sandstone channel within the panel and to forecast the size and location of sandstone rolls ahead of mining. Twelve geophones at approximately 10-m spacings were installed in the maingate. All geophones were installed horizontally on bolts grouted in the longwall panel rib. A 14-lb sledgehammer was used as a seismic source within the coal seam. Figure 5 shows the hammer sources located in the tailgate and on the longwall face (data from sources on the face only were accepted).

Velocity tomography was used to generate a reconstructed image from travel-time data. Average seismic velocity for the rocks at the mine was determined to be between 1,150 m/s (coal/shale) and 4,500 m/s (sandstone).

The tomographic images developed from the collected data are shown in Figure 5. The zone contours (4,500 m/s contours) indicate areas where the signal has traveled through sandstone. The tomograms were then verified by the mine geologist through on-site geologic evaluation.

At a relatively shallow Australian longwall coal mine, fracture zones were causing occasional guttering in front of shield canopies and consequent delays. Several roof falls occurred that extended up to 80 shields along the face. Position and severity of
roof falls were typically unpredictable. Rock3D™ was deployed to determine if roof structural anomalies or fracture zones, along with stress concentrations, could be readily mapped ahead of the face. The longwall panel investigated was 250 m wide by 1,900 m long, with a mining height of 4.2 m and an overburden depth of 170 m. Eight geophones were installed on roof bolts in the tailgate only of the longwall panel at 15-m spacings.

Tomograms developed from the data showed a pattern forming when roof falls occurred. A high stress zone developed at approximately 50 m ahead of the face, which created a high shear zone close to the face. Due to the weakness of the roof rock, failure then occurred. After the fall, the high stress zone moved closer to the face, and a smaller fracture zone was detected.

Figure 6 shows four consecutive tomograms indicating the pattern that developed. The first, at 3:55 to 4:09 p.m. shows areas of high attenuation (dark blue) indicating areas of fractured rock not under appreciable stress. An area of light green, indicating low attenuation and high stress, is developing around this blue region. In the next tomogram, for the period between 6:08 and 6:23 p.m., the area of high stress that probably represents the front abutment is further developing and looping around the fractured material toward the tailgate. The third tomogram at 6:59 to 7:17 p.m. shows the beginning of a second high-stress zone, and in the fourth tomogram at 10:32 to 11:14 p.m., the area of the high stress zone is expanding and spreading across the face.

During the period of these tomograms, sporadic hard cutting and yielding of shield legs occurred.

Subsequent tomograms show an increase in stress, which then migrates toward the main gate side of the face, and the cycle appears to terminate. For the two days following this, difficult face conditions were encountered, with significant spalling and guttering, and failure of most of the mid-face zone.

Over the following days, tomograms were produced that confirmed the pattern of stress abutment development, with stress circumscribing the tailgate corner. The
elevated stress zone appears to migrate toward the face until the rock became fractured and developed high attenuation, ultimately leading to failure on the face.

Image analysis and underground observation indicate that the extent of the mining-induced stress zone extended approximately 0.25 to 0.27 times the overburden depth (45-50 m). Significant mining-induced loads extend 0.1 times the overburden depth (18 m), the most critical zone is approximately 2 m from the face in the tailgate area. This agreed well with the Rock3D™ results. At this mine, Rock3D™ was considered a reliable tool in mapping patterns of stress buildup ahead of the mining face.

At another Australian longwall coal mine, a Rock3D™ study was conducted to determine if the system could predict periodic shield loading. The mine was experiencing difficulties with face control due to the onset of periodic loading on the shields, possibly caused by the presence of massive sandstone in the roof.

Figure 7 shows the tomograms that were produced from the study. The first tomogram (2/10/98, 11:12 a.m. – 12:34 p.m.) shows an elevated stress zone in the mid-face area, approximately 30-50 m from the face. High attenuation zones are shown on the outer portions of the area. The second image (2/11/98, 4:36 – 5:38 a.m.), covering a period of one hour early the next day, shows enlargement of the high stress zone from the previous day. The zone is similar in shape to the previous day, but has grown outward as the face approached. The third image (2/18/98, 5:20-6:25 a.m.), seven days later (the face only advanced a short distance due to production delays during the intervening period), shows that the high stress zone has changed shape slightly and moved closer to the face. The lower left lobe of high stress has faded away however. The fourth image, showing the situation 11 hours later, indicates a significant stress relief in the mid-part of the face. This suggests that the bridging sandstone had broken, lowering stress on the immediate face line. Areas of high stress developed to the lower left and right, similar to the pattern for the first image, indicating a cyclical pattern of stress development.

During the period monitored, failure of fractured roof rock ahead of the face was noted, which corresponded to the blue areas on the tomograms. The blue areas on the tomogram represent high attenuation, indicating that the rock had fractured, and was no longer competent.

The Rock3D™ images obtained during this short demonstration give an indication of the nature of cyclical weighting on the longwall face. A longer period of monitoring would be required to better define the exact nature of the loading.
Recent Rock3D™ Applications for Hard-Rock Mining

Following heavy rains over a mine in Western Australia, an extensive sinkhole developed above stopes along the strike of the ore zone in a nickel mine. The sinkhole, shown in figure 8, was nearly circular, with a diameter of about 60 m; the surface subsided to a depth of approximately 20 m within this diameter. The immediate concerns of the mining company were to determine the limits of the failed zone and to determine whether any perched mud or water zones existed. Apart from safety, this information was needed to assess the impact of the sinkhole on future mining operations.

![Image of sinkhole and boreholes](image)

**Figure 8.** Delineation of sinkhole/caved zone over a hard-rock mine.

Rock3D™ was used to delineate the extent of the fractured zone. Figure 8 shows a 3-D representation of the sinkhole and underground workings, the location of the sensors on the surface, and the borehole source locations. A series of shots was fired at various depths in each borehole, and the signals were received by the accelerometers on the surface and recorded by the Rock3D™ data acquisition system. The arrival times were processed to produce a series of 3-D tomographic images of wave velocity distributions in the rock mass (tomograms). The Rock3D™ code has the capability to produce 3-D contours at various velocities within the entire surveyed rock mass at any view angle. The figures shows 3-D velocity contours of 200, 400, and 600 m/s representing various material properties such as weak or highly fractured zones or mud-filled zones to consolidated rock mass. Combined velocity along any desired cross section can also be displayed. The top zone represents the weak area immediately below the sinkhole. It has a limited downward extent in this cross section. The pathway of the caved area, however, appears to have a slippage plane bounded by a fault structure on both sides. The middle zone coincides with the location of the only borehole identified by the drill logs to have a continuous water flow. This may represent an area containing perched mud or water, but based on the available mine data, it is not believed to have a large water volume. The lower dark zone coincides with the previously mined areas of the stope. Other cross sections were produced to give a more complete picture in areas of interest.

The tomographic images show the extent of fractured zone above the mine within the surveyed area. A funnel-shaped area was depicted below the sinkhole. This is a good example of the reliability of seismic tomography to map various degrees of rock...
competency above a mine area in 3-D. For the conditions at this mine, the technique produced fast, reliable results at a relatively low cost.

At a gold mine in the United States, chalcite cavities varying in size were encountered, impacting underground mine development and production. Rock3D™ was demonstrated to evaluate the viability of locating the extent of known cavities and to map other cavities ahead of mining. If successful, the company could use Rock3D™ for near-real-time imaging and evaluation of the rock mass on a mine-wide basis.

An area approximately 300 m ahead in the N-S direction and 120 m in the E-W direction was investigated. Seven geophones were installed at the 1075 level and eight geophones at the 1225 level, as shown in figure 9. The sensors were grouted in boreholes in pillar ribs. Hammer and blasting were used as seismic sources for the investigation. Velocity tomography was used to analyze the signals received. A 3-D image of the mine was created, which included the locations of drifts and headings, geophone positions, and the locations of known voids. Figure 9 shows the results of velocity tomography at the mine. The average seismic velocity in the mine was determined to be 9,500–10,000 m/s. For areas with no background coverage by seismic waves, a velocity contour of 7,500 m/s, shown in purple, indicates areas where voids may occur, and 12,500 m/s, in red, shows highly stressed zones.

The cavities that were imaged agreed well with existing cavities at the mine. The images also indicated areas of highly stressed rock surrounding the cavities. The project demonstrated that Rock3D™ could successfully image the location and extent of cavities in the mine with a certain accuracy, as well as the presence of high stress zones.

**Conclusions**

The conventional methods of identifying high stress areas and geologic anomalies have fallen far short of meeting both personnel safety requirements and the high
production demands of today’s mechanized mining operations. The Rock3D™
seismic tomography has evolved into a powerful predictive tool for continuous non-
intrusive assessment of ground conditions without interference to daily mining
operations, and without putting mine personnel at risk.

The use of the Rock3D™ seismic tomographic technology in various applications
worldwide have shown the high success and practicality of the system for delineating
ground hazards and structural instability ahead of mining.

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