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Roof-fall hazard field study using microseismic monitoring in a U.S. limestone mine

Roof falls are one of the major hazards of underground stone mining, causing injuries and fatalities. This paper examines the relationship between roof-fall events and microseismicity at an underground limestone mine. The study mine had adopted a proactive ground control approach in identifying and managing roof-fall hazards using a variety of procedures and techniques. Additionally, a surface-based microseismic monitoring system was installed to supplement the efforts of managing roof-fall hazards. The study results indicated that elevated levels of microseismicity were associated with roof falls at four-way intersections. However, observations indicated that roof falls caused by block fallout and skin failure were not associated with elevated levels of microseismicity. Additionally, the proactive ground control approach helped to anticipate a roof fall 3 days before the fall occurred. This paper presents a brief account of the geologic setting, mining conditions, ground control issues, and an examination of microseismicity associated with several roof falls that occurred in the study mine.

Introduction

The study mine, situated in central Pennsylvania, produces limestone using the room-and-pillar method of underground mining. One of the major hazards of underground mining is roof falls, which have the potential to cause injuries and fatalities. Fig.1 shows the incidence rate (number of injuries per 200,000 employee hours) of nonfatal days lost (NFDL) injuries related to roof falls in underground stone mines from 1997 through 2008 (MSHA, 2009). The average incidence rate of 0.33 for the most recent 6 years (2003 through 2008) compared to 0.58 for the previous 6 years (1997 through 2002) indicates a reduction in the injury rate. However, a rising trend has been noticed during 2006 through 2008. Roof instability in stone mines is often related to high horizontal stress and unfavourable geologic structures (Esterhuizen et al., 2007). Interaction of prominent joint sets with discontinuities and weak bedding planes can result in wedge failures or block fallout. Failure to recognize features contributing to roof instability potentially exposes miners to rockfall hazards.

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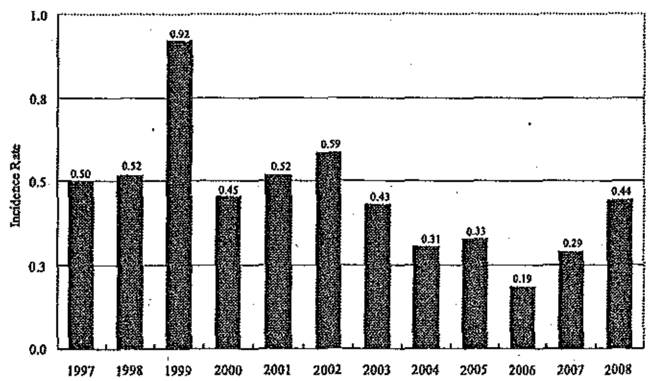

Fig.1 Incidence rate of nonfatal days lost injuries due to roof fall in underground stone mines (MSHA 2009)

Roof-fall hazards are inherent in underground stone mining and need to be managed and controlled. Iannacchione et al. (2006, 2007) developed a comprehensive technique for determining the roof fall risk index (RFRI) based on the observed values of ten defect parameters. The study mine used this technique to determine RFRI values for all areas where miners are required to work or travel. The mine implemented a proactive approach outlined in Appendix A for mitigating roof-fall hazards. Additionally, the mine installed a microseismic monitoring system to supplement roof-fall hazard assessment. It was anticipated that any clustering of microseismic events or substantial increase in the event rate should be viewed with caution. In a previous study at an underground limestone mine in western Pennsylvania, elevated levels of microseismicity were observed to be associated with major roof falls (Ellenberger and Bajpayee, 2007). If roof-fall hazards could be identified early, management personnel would be in a better position to control and manage such hazards.

Four case studies that occurred in the study mine—two intersection failures, one jointed block failure, and one skin failure—are presented in this paper. The two intersection failures involved complete collapse of the intersection area including several meters of roof strata above the normal roofline. Jointed block failure relates to the fall of a joint-bounded block of rock. Joint failures may be triggered by loss of confinement, stress redistribution due to mining, high horizontal stress, and deterioration of joint contact planes, and other causes. Skin failure is defined as rockfall from the surface of the roof to a depth of 0.6 m, but not limited in other dimensions (Tadolini and Dolinar, 2001).

Geologic setting and mining conditions

The study mine produces high-quality limestone from the Valentine member of the Linden Hall formation belonging to the Lower Middle Ordovician Limestones (Rones, 1969). The Valentine member is about 21.3 m thick in this area and is comprised of rocks from two closely related lithologic types. The upper 15.2 m section of strata consists of massive, light-gray calcilutites. The lower 6.1 m section is laminated with clay partings. About 9.1 m of a dark-gray and thinly bedded section of the Centre Hall member of the Nealmont formation lies above the Valentine Limestone (Rones, 1969). The Centre Hall Limestone is often laminated, and considered undesirable to constitute the immediate roof beam. Conversely, the top 1.8 m of the Valentine Limestone is massive and considered competent to form a stable roof beam.

A stress-control mine design plan was implemented in 2006 in the study mine to alleviate the effects of high horizontal stress. The design plan implementation included rectangular pillars having their long axes oriented parallel to the maximum horizontal stress direction with pillar sizes approximately 46 m long by 20 m wide. Additionally, crosscuts were staggered to develop three-way intersections. During development, rooms are driven to 15.2 m wide by 7.0 m high. Subsequently, an additional 11.3 m of limestone at the floor is mined by floor benching. All benched areas are regularly barricaded to prevent entry. The overburden thickness ranges from outcrop to approximately 320 m.

Proactive ground control

The study mine implemented a proactive ground control approach, outlined in Appendix A, to control and manage roof-fall hazards. The primary goals were safety of the workforce and serviceability of mine openings. The uniaxial compressive strength of Valentine Limestone ranges from 100 to 145 MPa, and the maximum horizontal stress in the area varies from 14.9 to 29.6 MPa in the N80°E direction (Esterhuizen and Iannacchione, 2004). Roof stability in stone mines is closely related to the thickness of the layer of rock in the immediate roof of the workings (Esterhuizen et al., 2007). In the study mine, the thickness of the immediate roof beam greatly influenced roof stability and the mine strived to maintain a stable roof beam by leaving a 1.8 m thick layer of Valentine Limestone. Additionally, the study mine routinely used a borescope to examine roof holes for assessing the thickness and integrity of the immediate roof beam. Stability of mine openings remains a major concern for production and safety at the study mine.

The RFRI values for all work and travel areas in the study mine, including escapeways, were routinely evaluated, according to the recommendations of Iannacchione et al. (2006, 2007). RFRI values were categorized into three levels—high, medium, and low—based on the observed values of defect parameters. Roof remediation efforts continued in areas of medium and high RFRI values. These efforts were particularly significant for a specific intersection where a roof fall occurred 3 days after a routine evaluation was completed. During the evaluation process, the thickness and integrity of the immediate roof beam was assessed. Based on the results of the assessment, the intersection was barricaded to prevent entry. After the roof fall, remediation activity and debris removal were completed.

Microseismic monitoring to examine ground instability

Background

Microseismic monitoring has long been used in the underground mining sector to examine ground stability issues. When a roof rock fractures or moves along a slip plane, it typically emits microseismic emissions. Miners have often noticed the association of popping or cracking noises with fracturing of roof strata. Obert and Duvall (1967) have long recognized that for every audible noise, an equivalent magnitude of microseismic emissions most likely occurs. Each of these emissions signifies the formation of a new rupture surface or slip on an existing fracture surface. Development of new fractures could lower the overall rock mass strength (Hardy, 1975). Therefore, elevated levels of seismicity generally signal development of potentially unstable ground conditions (Brady and Haramy, 1994).

During the past decade, the development of new microseismic monitoring techniques to characterize roof instability have been reported by Hayes (2000), Cai et al. (2001), Heasley et al. (2001), Iannacchione et al. (2004, 2005a), and Srinivasan et al. (2005). Ellenberger and Bajpayee (2007) studied the application of microseismic monitoring techniques for early detection of roof instability. The Moonee Colliery, situated north of Sydney, Australia, used microseismic monitoring techniques to study major gob-caving events associated with longwall mining (Hayes, 2000 and Iannacchione et al., 2005b). Development of ground instability can be associated with progression of microseismicity. Any clustering of seismic events or substantial increase in the seismic event rate should be viewed with caution. Having real-time access to rock fracture information on a continuous basis is a major advantage of microseismic monitoring.

A seismic event due to rock fracturing generates transient, dynamic, elastic waves that propagate through the surrounding rock mass. The p- and s-waves, also known as body waves, travel in a rock medium at characteristic velocities, C_p and C_s, given by the following equations (Persson et al., 1993), where C_p is the p-wave velocity (m/s), C_s is the s-wave velocity (m/s), E is the modulus of elasticity (GPa), í is the Poisson's ratio, and ñ is the density (kg/m^3) of the medium.

$$C_p = \left[\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}\right]^{1/2} \quad ...(1)$$

$$C_s = \left[\frac{E}{2(1+\nu)\rho}\right]^{1/2} \quad ...(2)$$

P-and s-wave velocities at the study mine were determined using several test blasts.

Mining-induced seismicity is generally related to shear and tensile fracturing caused by normal mining operations. Five modes of failure examined by Gale et al. (2001) are: (1) shear fracture through intact rock material; (2) tensile fracture through intact rock material; (3) shear fracture of bedding planes; (4) tensile fracture of bedding; and (5) remobilization of preexisting fractures. Generally, the compressive strength of a sedimentary rock is higher than its tensile strength. Consequently, seismic energy emission due to shear/compressive failures is higher than the energy emitted due to tensile failures. Due to high-energy content, microseismic emissions due to shear/compressive failures can propagate farther than tensile failures. Therefore, low-energy tensile failures occurring away from the sensor array may not be detected and located properly unlike high-energy shear/ compressive fractures.

Microseismic monitoring system at the study mine

A surface-based microseismic system was installed at the study mine in 2007 to monitor microseismic emissions associated with roof-caving events. The study mine considered microseismic monitoring as an additional tool for identifying roof-fall hazards. Eight triaxial geophones were installed in four boreholes drilled from the surface. The microseismic system consists of a central site, located at the mine office, and four borehole sites distributed over the mine property. At each borehole site, a local data-acquisition station was installed with its processor unit, power supply, radio communication, global positioning system (GPS) timing unit, and two geophones.

The computer at the central site interfaced with the four borehole stations for real-time data acquisition and processing. The central site controls each borehole site, and continuously monitors the seismic array. Each borehole data-acquisition station is powered by a battery pack containing six 12-volt, rechargeable batteries. A twin-unit solar panel recharges the battery pack. At each borehole station, the solar panel is mounted on the roof of the instrument housing. The essential system components at a borehole site are shown in Fig.2. All four borehole stations are synchronized and seismic signals are recorded on a common time base. The frequency response of the geophones ranged from 15 to 1,000 Hz.

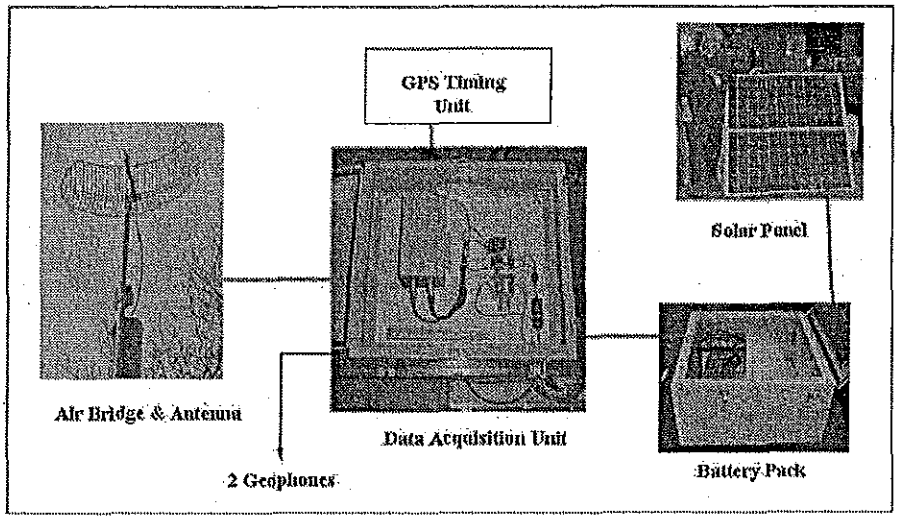

Fig.2 Essential system components at a borehole site

Microseismicity associated with roof falls

Microseismicity associated with roof falls at two intersections, a block fallout involving a jointed-roof structure, and a skin failure were detected by the monitoring system. The seismic data analysis was completed after each roof-fall event.

Intersection failure on October 22, 2007

A roof fall occurred at a four-way intersection in an abandoned part of the mine on October 22, 2007. During a routine inspection, airborne dust was observed near the southeastern part of the mine. As the inspection progressed, it was observed that several brattices were knocked down. Upon further examination, it was noticed that the roof at two adjacent four-way intersections had collapsed. The entire intersections from the bottom of the benched floor to the top of the roofline were filled with fallen roof debris. The roof cavity extended an estimated 18.5 m above the normal roofline at both intersections. The pillars around these two fall areas were intact and did not show any visible signs of damage due to the impact of falling roof debris or stress redistribution pursuant to the roof falls. These intersections were drifted in November 2001, benched in June 2006, and barricaded in July 2006.

Fig.3 shows a plot of microseismic emissions detected during this roof-fall event. As stated earlier, data analysis was not done in real time but within a few days after the roof-fall event. The overall microseismicity rate during the roof-fall was 1.4 events/hour; in comparison, the background seismicity rate for the entire mine before this fall seldom exceeded three

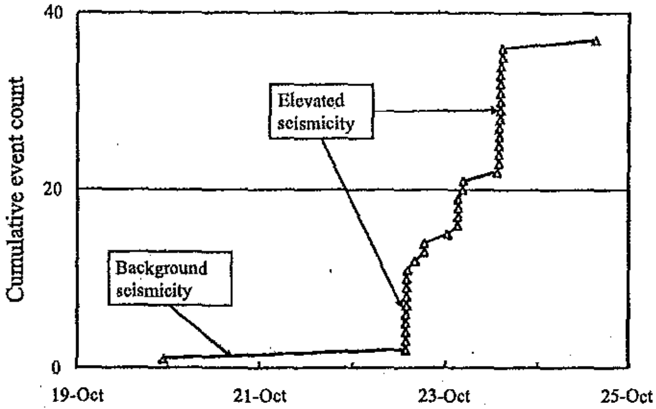

Fig.3 Cumulative plot of microseismic emissions associated with intersection failure on October 22, 2007

events per day. The first roof-fall impact signature was observed about 10 minutes after the onset of an elevated level of microseismicity. Several more roof-fall impacts events followed the first impact.

INTERSECTION FAILURE ON MAY 22, 2009

On May 22, 2009, another roof fall occurred at a four-way intersection that was inspected 3 days before the fall and found to have adverse roof conditions. The area was, subsequently, barricaded to prevent entry. The borescope inspection detected voids and layer separation at the anchorage level of roof bolts. The size of the fall area was approximately 20 m by 23 m and the roof cavity extended about 3 m above the normal roofline. The borescope inspection provided indication early enough to abandon the area and withdraw workers. The roof separation occurred primarily at the fractured horizon observed during the borescope inspection. This roof fall did not cause injury of personnel, entrapment of any miner, or impairment of ventilation or escapeways. No underground equipment was involved in the roof fall. The roof-fall debris did not go beyond the barricade installed prior to the fall.

Fig.4 shows a plot of microseismic emissions detected during this roof-fall episode. The overall microseismicity rate

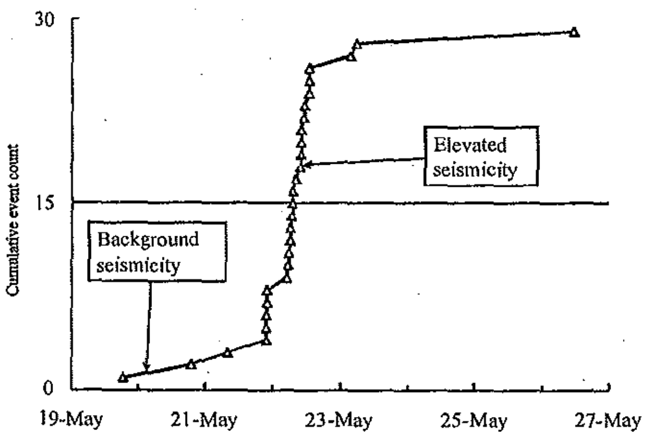

Fig.4 Cumulative plot of microseismic emissions associated with intersection failure on May 22, 2009

during the roof-fall episode was 0.7 events/hour compared to the background seismicity level before and after this fall that seldom exceeded three events per day. The first roof-fall impact signature was observed about 9 hours after the onset of the elevated level of microseismicity. Several additional roof-fall impact signatures were recorded during this roof-fall episode. Again, an elevated level of microseismicity could have provided an indication of the approaching roof-fall hazard.

JOINTED BLOCK FALLOUT ON MARCH 18, 2009

A jointed block fallout occurred approximately 15 m from an active working face and 21m from the nearest three-way intersection. The area of roof that fell down was approximately 12m wide by 15m long. Several joints in the roof, oriented diagonally across the fall area, were clearly visible. Interaction of open joints with weak bedding planes could cause block fallout. This block fallout did not cause any personnel injury, entrapment of any miner, or impairment of ventilation or escapeways. No underground equipment was involved in this block fallout. Eight microseismic emissions related to rock fracturing were detected in a 2-hr period before the block fallout.

SKIN FAILURE ON MARCH 31, 2009

A skin failure occurred in a part of the mine that was developed before 1953. A piece of roof rock ranging in thickness from 7 to 15 cm fell down at a four-way intersection. It was concluded that due to exposure—over 50 years—to the elements, the piece of rock fell down after losing its bonding strength. Subsequently, the fall area was cleared and the roof was stabilized. Two microseismic emissions were recorded during this skin-failure episode. The difficulty in detecting low-energy tensile fractures associated with failure due to loss of bonding strength may explain, in part, the lack of microseismicity during this skin-failure episode.

Summary and conclusions

Roof falls represent a major hazard in the underground stone mining sector. The stability of mine openings is a major concern for maintaining safety and productivity in underground stone mines. The study mine adopted a proactive approach for managing and controlling roof-fall hazards, and identified microseismic monitoring as an effective tool for roof-fall hazard assessment. A major advantage of microseismic monitoring is that it provides real-time access to rock fracture information on a continuous basis. Additionally, the RFRI method of roof fall hazard assessment assisted in identifying and quantifying roof fall hazards.

This study provided an avenue for examining the association of microseismicity with major roof falls. Study results showed that elevated levels of microseismicity were associated with roof falls at intersections. However, rockfalls comprising a block fallout and a skin failure were not observed to be associated with similar levels of microseismicity. Additionally, a proactive ground control approach helped to anticipate a roof fall 3 days before the fall occurred. A timely understanding of impending roof-fall hazards has been a goal of ground control professionals. This study found that real time microseismic monitoring could be used to supplement the effort of examining roof-fall hazards. The results of this study are encouraging for further exploration toward implementing a comprehensive ground control plan.

Disclaimer

The findings and conclusions in this paper have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

References

1. Brady, B. T. and Haramy, K. Y. (1994): "High Amplitude Stress Wave Generation and Damage Induced by Roof Caving in Mines." Proceedings of the First North American Rock Mechanics Symposium, University of Texas, Austin, TX, June, pp. 1033-1040.
2. Cai, M., Kaiser, P. K. and Martin, C. D. (2001): "Quantification of Rock Mass Damage in Underground Excavations from Microseismic Event Monitoring." *International Journal of Rock Mechanics and Mining Sciences*, Vol. 38, pp. 1135-1145.
3. Ellenberger, J. L. and Bajpayee, T. S. (2007): "An Evaluation of Microseismic Activity Associated with Major Roof Falls in a Limestone Mine: a Case Study." 2007 SME Annual Meeting and Exhibit, February, Denver, Colorado, preprint 07-103, Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc., Feb, pp. 1-5.
4. Esterhuizen, G. S. and Iannacchione, A. T. (2004): "Investigation of Pillar-Roof Contact Failure in Northern Appalachian Stone Mine Workings." Proceedings of the 23rd International Conference on Ground Control in Mining, Morgantown, WV, West Virginia University, August, pp. 320-326.
5. Esterhuizen, G. S., Dolinar, D. R., Ellenberger, J. L., Prosser, L. J., and Iannacchione, A. T. (2007): "Roof Stability Issues in Underground Limestone Mines in the United States." Proceedings of the 26th International Conference on Ground Control in Mining, Morgantown, WV, July-Aug., pp. 336-343.
6. Gale, W. J., Heasley, K. A., Iannacchione, A. T., Swanson, P. L., Heatherly, P. and King, A. (2001): "Rock Damage Characterization from Microseismic Monitoring." Proceedings of the 38th U.S. Rock Mechanics Symposium, Vol. II, Washington, D.C., July, pp. 1313-1320.
7. Hardy, R. (1975): "Emergence of AE/MA as a Tool in Geomechanics." First Conference on Acoustic Emission-Microseismic Activity in Geologic Structures and Materials, University Park, PA, June, Series on Rock and Soil Mechanics, Vol. 2, No. 3, by Trans Tech Publications, Rockport, MA, pp.13-31.
8. Hayes, P. (2000): "Moonee Colliery: Renewing the Economic Viability of a Mine Using Microseismic and Hydraulic Fracturing Techniques." Proceedings of the 19th International Conference on Ground Control in Mining, Morgantown, WV, West Virginia University, August, pp. 38-44.
9. Heasley, K. A., Ellenberger, J. L. and Jeran, P. (2001): "An Analysis of Rock Failure Around a Deep Longwall Using Microseismics." Proceedings of the 20th International Conference on Ground Control in Mining, Morgantown, WV, West Virginia University, August, pp. 280-286.
10. Iannacchione, A. T., Coyle, P. R., Prosser, L. J., Marshall, T. E. and Listenberger, J. (2004): "The Relationship of Roof Movement and Strata-Induced Microseismic Emissions to Roof Falls." 2004 SME Annual Meeting and Exhibit, February, Denver, Colorado, preprint 04-58. Littleton, CO. Society for Mining, Metallurgy, and Exploration, Inc., pp. 1-9.
11. Iannacchione, A. T., Esterhuizen, G. S., Bajpayee, T. S., Swanson, P. L. and Chapman, P. C. (2005a): "Characteristics of Mining-Induced Seismicity Associated with Roof Falls and Roof Caving Events." Proceedings of the 40th U.S. Rock Mechanics Symposium, Anchorage, AK, June, Alexandria, VA, American Rock Mechanics Association, June, pp. 1-10.
12. Iannacchione, A. T., Bajpayee, T. S. and Edwards, J. L., (2005b): "Forecasting Roof Falls with Monitoring Technologies – a Look at the Moonee Colliery." Proceedings of the 24th International Conference on Ground Control in Mining, WV, West Virginia University, August, pp. 44 - 51.
13. Iannacchione, A. T., Esterhuizen, G. S., Schilling, S. C. and Goodwin, T. (2006): "Field Verification of the Roof Fall Risk Index: a Method to Assess Strata Conditions." Proceedings of the 25th International Conference on Ground Control in Mining, WV, West Virginia University, August, pp. 128-137.
14. Iannacchione, A. T., Prosser, L. J., Esterhuizen, G. S. and Bajpayee, T. S. (2007): "Technique to Assess Hazards in Underground Stone Mines: The Roof Fall Risk Index (RFRI)," *Mining Engineering*, Vol. 59, No. 1, pp. 49-57.
15. MSHA (2009): Accident, Illness and Injury and Employment Self-Extracting Files (Part 50 Data), 1997–2008. Denver: U.S. Department of Labor, Mine Safety and Health Administration, Office of Injury and Employment Information.
16. Obert, L. and Duvall, W. I. (1967): Rock Mechanics and the Design of Structures in Rock. John Wiley and Sons, Inc., New York, NY, pp. 113-188.
17. Persson, P., Holmberg, R. and Lee, J. (1993): Rock Blasting and Explosives Engineering. CRC Press, New York, NY, pp. 342.
18. Rones, M. (1969): "A Lithostratigraphic, Petrographic and Chemical Investigation of the Lower Middle Ordovician Carbonate Rocks in Central Pennsylvania," General Geology Report G 53, Bureau of Topographic and Geologic Survey, Commonwealth of Pennsylvania.
19. Srinivasan, C., Sivakumar, C. and Gupta, R. N. (2005): "Source Parameters of Seismic Events in a Coal Mine in India." In: 27th Seismic Research Review: Ground Based Nuclear Explosion Monitoring Technologies, Rancho Mirage, California, September.
20. Tadolini, S. C., Dolinar, D. R. (2001): "Enhanced Surface Control for Roof and Rib Stability." Proceedings of the 20th International Conference on Ground Control in Mining, WV, West Virginia University, August, pp.173-179.

Elements of proactive ground control

Work areas: Inspect face, roof, and rib areas in each heading where miners are working or scheduled to work. Communicate observations to miners and foreman. Pay particular attention to any changes in lithology, bedding planes, joint systems, faults, and secondary minerals. Communicate all information to the next shift and engineering. Follow approved procedures for all roof inspection, monitoring, support, and repair works.

Roof fall risk index (RFRI): Evaluate RFRI for all areas where miners work and travel and plot RFRI values on mine map. Take remedial actions to mitigate hazards in areas of high and medium RFRI. RFRI should be reduced to an acceptable level or the area should be barricaded to prevent unauthorized entry.

Drilling, blasting, and mechanical scaling: Record all observations in the drilling, blasting, and scaling logs. Pay particular attention to geologic anomalies. Scaling report must be communicated to the next shift and engineering.

Haulage, escapeways, portals, and work stations: Inspect regularly haulage, escapeways, portals, and all underground work stations. Record observations and communicate information to the next shift and engineering.

Roof bolting: Observe for drill speed, dust, and water consumption. Communicate information to the next shift and engineering. Use scratch tool to detect fractures in roof holes, and record crack location (depth) and extent of strata separation. Communicate information to the next shift and engineering.

Thickness of immediate roof beam: Thickness and integrity of the immediate roof beam must be determined by drilling holes in the roof and examining each hole using video borescope. Data must be recorded, shown on the mine map, and communicated to the next shift and engineering.

Extensometers: Install extensometers or roof sag monitors to measure roof deflection. Record all observations related to roof deformation. Communicate information to the next shift and engineering.

Roof falls, gutters, and changes in strike or dip: Roof falls, roof gutters, and any changes in the strike or dip (direction or magnitude) must be located and shown on the mine map. Their effect on ground stability should be evaluated.

Microseismic monitoring: Check the display screen to examine the location and frequency of microseismic emissions. Pay particular attention to spatial clustering and an elevated level of microseismicity.

INTEGRATED DESIGN CRITERIA FOR EVALUATION OF SUPPORT PERFORMANCE AND ESTIMATION OF SUPPORT CAPACITY REQUIREMENT FOR LONGWALL WORKINGS

(Continued from page 320)

28. Singh, G. S. P. and Singh, U. K. (2009a): "Numerical modelling based assessment of setting load requirement for optimum performance of powered roof supports in longwall workings", *Mining Technology* (Section A), 118, 2, 109-114.
29. Singh, G. S. P. and Singh, U. K. (2009b): "Assessment of Dynamic Loading and Rapid Yield Valve Requirement for Powered Roof Supports in Longwall Workings", *Mining Technology* (Section A), 118, 1, 47-52.
30. Singh, G. S. P. and Singh, U. K. (2009c): "A Numerical Modelling Approach for Assessment of Progressive Caving of Strata and Performance of Hydraulic Powered Support in Longwall Workings", *Computers and Geotechnics*, 36, 1142-1156.
31. Singh, G. S. P. and Singh, U. K. (2009d): "Numerical Modelling Study of the Effect of Some Critical Parameters on Caving Behaviour of Strata and Support Performance in a Longwall Working", *Rock Mechanics and Rock Engineering*, DOI 10.1007/s00603-009-0061-1.
32. Singh, G. S. P. and Singh, U. K. (2010): "Prediction of caving behaviour of strata and optimum rating of hydraulic powered support for longwall workings", *International Journal of Rock Mechanics and Mining Sciences*, 47, 1-16.
33. Smart B. G. D. and Redfern, A. (1986): "The evaluation of powered support specification from geological and mining practice information", Proc: Rock Mechanics: Key to Energy Production: 27th US Symposium on Rock Mechanics, The University of Alabama, Tuscaloosa, Alabama, June 1986, 367-377.
34. Smart, B. G. D. and Aziz, N. I. (1986): "The influence of caving in the Hirst and Bulli seams on powered support rating", Proc: Symposium on Ground Movement and Control related to Coal Mining, The Australian Institute of Mining and Metallurgy, Illawara Branch, University of Wollongong, Australia, August 1986, 1-12.
35. Smart, B. G. D., Isaac, A. K. and Hinde, C. G. (1980): "Investigations into the relationship between powered support performance and the working environment with particular reference to strata convergence", Proc: 21st US Symposium on Rock Mechanics, University of Rolla, May, 332-344.
36. Smart, B. G. D., Sommerville, J. M. and McGraw, W. M. (1987): "Instrumentation for monitoring powered support behaviour", *Mining Science and Technology*, 5, 153-161.
37. Wilson, A. H. (1975): "Support load requirements on longwall faces", *Mining Engineer*, 134, June, 479-488.
38. www.vts.de, accessed: 09 October 2006.