Microseismic management for macro-scale benefits

Ian Leslie explains how slope monitoring can mitigate the economic and safety risks associated with instability and extend mine life at open-pit operations

Figure 1: deployment of geophone arrays down vertical boreholes

The economic benefits and high production capacity associated with large surface-mining operations have made open-pit mining a widely applied recovery method, particularly for large deposits of lower-grade ore that cannot be mined economically with underground methods.

Economic production depends on careful pit design that optimises the size of the mine, including the depth and steepness of pit slopes. Pit design, therefore, should consider not only ore distribution and production costs, but also rock-mass strength and stability.

Slope stability in open-pit mines presents a significant economic and safety risk to operations, and must be managed from the early stages of mine planning and design, and throughout the life of the mine. Bench or high-wall failures and rock falls can result in injury to or death of workers, loss of equipment or permanent or temporary shut-down of production operations. Slope stability remains a concern in even the most conservative slopes, due to the unknown physical properties and conditions of the rock mass beneath the slope surface.

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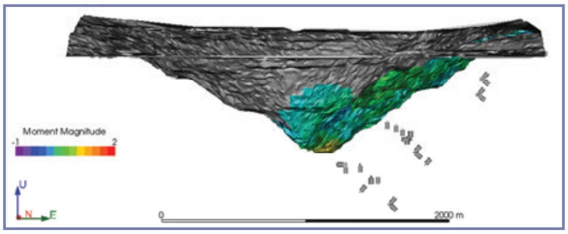
Open-pit mining depths have continued to increase and some operations now exceed depths of 1,000m. It is understandable then that risk management associated with slope stability is a primary concern as mines extend deeper and pit walls become steeper. Increased mining depths introduce greater risk of stability issues, since stress levels are considerably higher in the in-situ rock mass, particularly at the slope toe.

MONITORING TECHNIQUES

Monitoring systems are an essential component of any risk-management programme. Early detection of instability can significantly reduce the risk of injury, death and economic loss. Slope behaviour in open-pit operations is currently monitored with a variety of geotechnical tools. Most methods evaluate slope deformation by visual inspection of the slope surface.

Figure 2: location of uniaxial (single grey blocks) and triaxial (groups of three grey blocks) sensors installed behind an open-pit wall



Methods such as radar and laser scanning, prism-based surveying and measurement with extensometers or inclinometers can evaluate displacement at a failure surface with high accuracy and frequency, but are typically short-term solutions that may be affected by atmospheric conditions. Surface-based methods only evaluate 2-D deformation of the slope surface and do not reveal details about the conditions within the rock mass that might initiate instability.

In contrast, subsurface methods including borehole extensometers, inclinometers, piezometers and microseismic monitoring can provide deeper insight into the stress conditions and behaviour of the rock deep within the pit walls. Subsurface methods evaluate and track fractures within the rock mass as they develop and before they manifest on the surface.

Studies have demonstrated that subsurface seismicity can be detected weeks before instability occurs at the surface, and investigation into the mechanism of rock failure behind pit walls may help to understand the behaviour and trigger mechanisms responsible for future slope failure.

Regardless of the method, slope monitoring systems are critical components of any open-pit mining operation. An ideal monitoring approach for slope stability would implement both surface-based and subsurface methods for a comprehensive understanding of rock mass behaviour.

Implementing a monitoring system such as a microseismic network early in mining operations provides an opportunity to assess normal background seismicity, and easily identify abnormal behaviour.

MICROSEISMIC METHODS

Microseismic monitoring is probably best known in the mining industry as a diagnostic and safety tool for underground operations in hard-rock mines. Unlike large-scale earthquakes that can be felt on the surface, micro-earthquakes (or microseisms) are very small and usually range from -4 to 0 on the magnitude scale. These micro-earthquake events occur as a result of changing stress distributions in the rock mass.

Rock failures in the form of small fractures or shear stress slippages along pre-existing faults and fracture networks release energy that is detectable by sensitive monitoring equipment positioned around the production zone. Sensor arrays are deployed to monitor or ‘listen’ to the microseismic activity generated in the rock. The microseismic energy released can then be processed in real-time and located and mapped in 4-D (x, y, z plus time).

Seismic monitoring of underground mines has been employed for over 30 years. Original research activities in the field of microseismicity during the early 1980s were focused on predicting rock burst and roof fall in underground mines; however, in recent years, the techniques for evaluating induced seismicity have been successfully applied to hydro-fracturing processes in oil and gas or geothermal operations, structural health monitoring of dams and bridges and the evaluation of slope stability in open-pit mines.

In response to a greater need for monitoring tools in increasingly deeper open-pit mines, the recent application of microseismic techniques has been made possible by advances in technology and computing power.

The first successful microseismic

monitoring of open-pit operations dates back to 2002, when the Cripple Creek and Victor mine, operated by AngloGold in Colorado, US, installed an eight-channel ESG Hyperion System to monitor a volume of rock measuring 200m x 200m x 200m during the wall retreat. The system assisted the mine personnel to quickly identify when a sill behind the wall face became seismically active and then incorporate this information into the planning of the subsequent mine development.

Typically, open-pit microseismic systems are permanently deployed to monitor a single pit wall or specific zone that is experiencing slope failure. Sensor arrays are designed to provide a well-distributed network with good 3-D coverage of the monitored rock mass. The size of the array is dependent on available mine infrastructure.

Most open-pit monitoring systems are restricted to sensors deployed from the surface. Signals must propagate to sensors at the surface, especially in mines of extreme pit depth, and are subject to high signal attenuation due to the presence of overburden, as well as the highly fractured nature of the rock. Ideally, sensor arrays are deployed as vertical tool strings within long boreholes hundreds of metres deep, where they are grouted in place for good coupling to the wellbore.

In this case, sensors are positioned much closer to the target monitoring zone, reducing signal attenuation. At depth, consolidated rock is more conducive for high-frequency signal transmission. ESG has deployed borehole arrays to a depth of 2,500m (see Figure 1).

If ramps or tunnels are accessible behind the pit walls, sensors may also be installed in deviated boreholes extending from the underground infrastructure. Figure 2 demonstrates the location of uniaxial and triaxial sensors installed from the surface, as well as from existing underground infrastructure, to achieve good coverage of one wall of an open-pit mine.

Typically, 15Hz geophones are used for their low-cost reliability in harsh mining environments and performance over the range of frequencies associated with microseismic events in open-pit operations. Signals are transmitted from the sensors to surface-based Paladin data loggers via copper cables. At the surface, the data acquisition units are housed in junction boxes within stand-alone stations complete with power supply (solar) and GPS for time synchronisation of the signals (see figure 3).

Data is then transmitted to a central acquisition workstation located within the engineering office via radio, or a fibre-optic network if available, where data is automatically processed and seismic events are triggered in real-time. Events are then located in 3-D and parameters such as seismic magnitude are determined.

APPLICATIONS

The primary applications for microseismic slope monitoring include the evaluation of fractures generated during mining applications, activation of known or unknown geological structures in the rock mass, stress changes behind the slopes, evaluation of vibration thresholds of the slope structure and before any transition from open-pit to underground mining.

As in-situ stresses change in the rock mass during blasting or bench retreat, small fractures develop. While most of this activity occurs deep within pit walls and remains undetected, some fractures may propagate to the pit walls. Microseismicity associated with these fractures can be detected and used to track fracture locations, contributing to knowledge of potential zones of weakness during wall retreat and serving as valuable input for mine planning.

Geological structures are often locked in place by the stresses and confinement of the surrounding rock mass. The act of removing large volumes of rock during mining may reduce the confinement on small joint sets or larger shear/fault zones, resulting in fracture expansion and/or movement on existing larger structures. This activity can be associated with considerable microseismic activity or large-magnitude fault slips. A microseismic system determines the location and magnitude of these activities in real-time, potentially acting as an early warning system by detecting abnormal seismic activity weeks before displacements are observed at the surface.

Another important factor to consider in open-pit stability is how the slope responds to high levels of vibration. Any slope can be mobilised if it is subjected to a sufficient impulse of energy due to blasting or nearby seismicity (earthquakes). Energy levels are often characterised by predicted levels of peak-particle velocity (PPV) or acceleration (PPA). Seismic equipment can measure PPV and PPA values of larger events and trigger alerts if signals exceed thresholds defined as critical to slope stability.

Uniform hazard spectra analysis is another tool that can be used to assess slope stability. Over time, a seismic system generates a database highlighting the relationship between response spectra and the severity of any damage on slope surfaces. Specific design criteria can be developed for slopes in different regions of a mine, and alerts can be issued based on threshold limits.

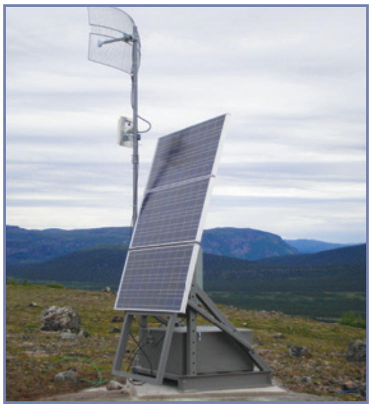


Figure 3: stand-alone remote data-acquisition station equipped with GPS, solar power and radio transmission. Paladin data loggers are housed within NEMA-4 junction boxes at the base of the unit

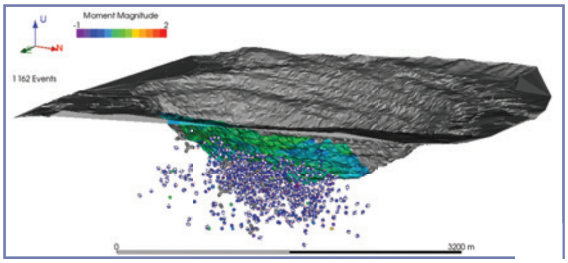


Figure 4: microseismic events detected over a four-month period behind the eastern wall of a deep open-pit mine experiencing slope instability

ACTIVATING STRUCTURES

In a large open-pit mine in South America, a 36-channel ESG Paladin microseismic array was deployed to monitor a volume of rock approximately 1,000m x 1,500m x 1,000m within the eastern pit wall. The array consisted of nine triaxial and nine uniaxial 15Hz omni-directional geophones, and was used to evaluate the correlation between occurred seismicity, major geological features and general mining activity that could affect both present operations and strategic mine planning.

Over a period of four months, a total of 886 seismic events with moment magnitudes between -1.2Mw and 1.4Mw were recorded and located to within an average accuracy of 28m. Individual event locations were calculated using automatic first-arrival picking algorithms, and advanced location techniques were employed to further improve the accuracy of event location.

The results indicated that local geological structures were seismically active, with the majority of seismicity occurring in two narrow bands located just inside the eastern wall, approximately parallel to its face. Figure 4 depicts microseismic events located behind and below the pit wall.

EXTENDING MINE LIFE

Although many open-pit operations have achieved dramatic production volumes by descending to new depths, often the orebody cannot be fully recovered using surface methods alone. In these cases, some mines may decide to extend production of the orebody by transitioning

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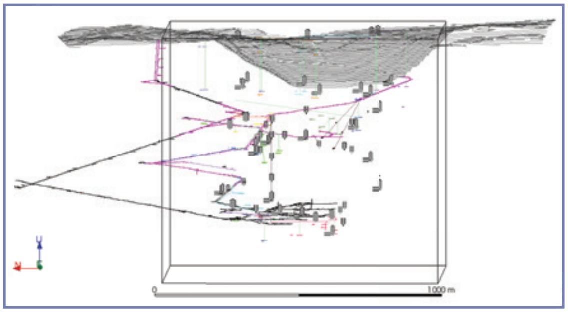

Figure 5: microseismic sensor array configured to monitor block-caving operations beneath a decommissioned open pit

operations to continue underground.

Methods such as block or panel caving can offer cost-effective mass-production of high volume, low-grade ore and effectively prolong the mine's operational life. Example sites that have or are planning to make this transition include the Palabora Mining Co in South Africa, Codelco's Chuquicamata copper mine in Chile, and Freeport McMoRan Copper and Gold's Grasberg mine in Indonesia.

This practice is not without considerable challenges. The presence of the large open-pit introduces regions of stress concentrations and low confinement that may significantly impact subsequent underground operations. In particular, high stresses may increase the likelihood of induced seismicity, particularly rock bursts.

Whether an open-pit mine remains in operation or is decommissioned, the implementation of a microseismic system to monitor underground operations beneath the pit can offer considerable information regarding rock mass behaviour and serve as an essential safety tool.

Open-pit mines that have implemented an open-pit microseismic monitoring system can expand the existing network to effectively monitor underground operations as they initiate beneath the pit. Figure 5 depicts a microseismic system that is now used to monitor block caving operations beneath a decommissioned open-pit. As caving operations migrate upwards towards the base of the open-pit, the rock mass beneath the pit floor will be subject to higher stresses that may impact the rate of caving propagation by either accelerating or halting the process.

If operations are designed to occur simultaneously in the open pit and underground, a stable crown pillar or equivalent must remain intact to separate the pit floor and cave back. A microseismic system can track the progression of the cave front as it advances, as well as the development of any subsidence crater at the pit base that might impact a region of the mine beyond the perimeter of the pit and might grow over time. Care will need to be taken to understand how this subsidence affects any surface infrastructure related to open-pit operations.

SUMMARY

As the depths of open-pit operations continue to increase, stresses within and beneath pit walls can cause considerable instability on slope surfaces. Monitoring systems represent an essential tool to mitigate economic and safety risk associated with slope failure. Despite the fact that seismic monitoring of underground mines is well established, the application of this technology to monitor open-pit mines is relatively recent.

The knowledge of seismicity behind pit walls offers engineers an excellent opportunity to evaluate rock-mass behaviour, track fracture propagation and potentially predict slope stability issues before they manifest on the surface. Natural expansion of microseismic systems can be used to aid the transition from large open-pit operations to underground mass mining, during which considerable seismicity is expected.

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