DETECTING PROBLEMS WITH MINE SLOPE STABILITY

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ABSTRACT

Slope stability accidents are one of the leading causes of fatalities at U.S. surface mining operations. The Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) is currently conducting research to reduce the fatalities associated with slope failures. The purpose of this paper to discuss some of this research and to present potential new technologies for slope monitoring and design. The paper also briefly discusses various warning signs of slope instability, introduces the most common slope monitoring methods, describes the limitations of various slope monitoring systems, and presents some field results using some of this new technology.

CONSEQUENCES OF SLOPE FAILURES

Whether on the surface or underground, unanticipated movement of the ground can pose hazardous conditions which may lead to endangerment of lives, demolition of equipment, and the loss of property. In the five years since 1995, 33 miners have lost their lives as a result of surface ground control accidents (see Figure 1). As such, the National Institute for Occupational Safety and Health's (NIOSH) Office of Mine Safety and Health Research in Spokane, Washington has initiated a research program with the goal of reducing the number of injuries and fatalities resulting from slope failures at mines.

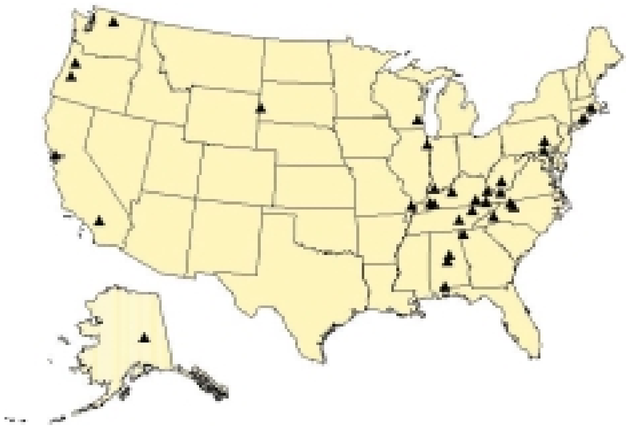

Figure 1. Map of 33 fatalities occurring from surface ground control problems January 1995 -June 2000.

There are several ways to reduce the chances of surface ground control failures: 1) safe geotechnical designs; 2) secondary supports or rock fall catchment systems; or 3) monitoring devices for advance warning of impending failures. While it is important to note that geotechnical designs can be improved to increase factors of safety, proper bench designs can be improved to minimize rock fall hazards, and certain support systems may enhance overall rock mass strength, diligent monitoring and examination of slopes for failure warning signs is the most important means of protecting exposed mine workers. Even the most carefully designed slopes may experience failure from unknown geologic structures, unexpected weather patterns, or seismic shock (Figure 2).

Figure 2. Consequences of unexpected slope failures.

SLOPE MONITORING SYSTEMS

Relative displacement measurements are the most common type of monitoring, complemented by monitoring of groundwater. The most important purpose of a slope monitoring program is to: 1) maintain safe operational practices; 2) provide advance notice of instability; and 3) provide additional geotechnical information regarding slope behavior (Sjöberg, 1996). The following is a list of the most common monitoring systems currently in use and is not intended to be an all-inclusive list of monitoring equipment. Readers interested in a more comprehensive list are referred to Szwedzicki, 1993.

Surface Measurements

Survey Network: A survey network consists of target prisms placed on and around areas of anticipated instability on the slopes, and one or more non-moving control points for survey stations. The angles and distances from the survey station to the prisms are measured on a regular basis to establish a history of movement on the slope. It is extremely important to place the permanent control points for the survey stations on stable ground. The surveys can be done manually by a survey crew or can be automated.

Tension Crack Mapping: The formation of cracks at the top of a slope is an obvious sign of instability. Measuring and monitoring the changes in crack width and direction of crack propagation is required to establish the extent of the unstable area. Existing cracks should be painted or flagged so that new cracks can be easily identified on subsequent inspections. Measurements of tension cracks may be as simple as driving two stakes on either side of the crack and using a survey tape or rod to measure the separations.

Another common method for monitoring movement across tension cracks is with a portable wire-line extensometer (Figure 3).

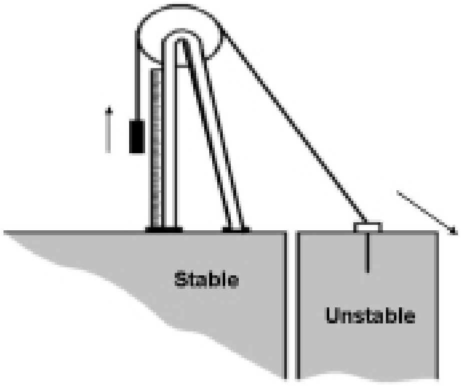

Figure 3. Portable wire-line extensometer for monitoring a tension crack.

The most common setup is comprised of a wire anchored in the unstable portion of the ground, with the monitor and pulley station located on a stable portion of the ground behind the last tension crack. The wire runs over the top of a pulley and is tensioned by a weight suspended from the other end. As the unstable portion of the ground moves away from the pulley stand, the weight will move and the displacements can be recorded either electronically or manually. Long lengths of wire can lead to errors due to sag or to thermal expansion, so readjustments and corrections are often necessary. The length of the extensometer wire should be limited to approximately 60 m (197 ft) to keep the errors due to line sag at a minimum (Call and Savely, 1990).

Subsurface Measurements

Inclinometers: An inclinometer (figure 4) consists of a casing that is placed in the ground through the area of expected movements. The end of the casing is assumed to be fixed so that the lateral profile of displacement can be calculated. The casing has grooves cut on the sides that serve as tracks for the sensing unit.

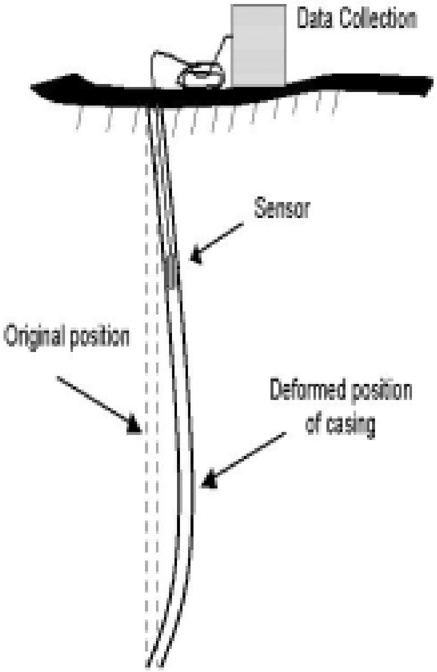

Figure 4. Cross-sectional schematic of typical traverse-probe inclinometer system.

The deflection of the casing, and hence the surrounding rock mass, are measured by determining the inclination of the sensing unit at various points along the length of the installations. The information collected from the inclinometers is important to slope stability studies for the following reasons (Kliche, 1999):

- to locate shear zone(s);
- to determine whether the shear along the zone(s) is planar or rotational;
- to measure the movement along the shear zone(s) and determine whether the movement is constant, accelerating, or decelerating.

Time Domain Reflectometry (TDR): Time Domain Reflectometry is a technique in which electronic pulses are sent down a length of a coaxial cable. When deformation or a break in the cable is encountered, a signal is reflected giving information on the subsurface rock mass deformation. While inclinometers are more common for monitoring subsurface displacements, TDR cables are gaining popularity and have several advantages over traditional inclinometers (Kane, 1998):

- Lower cost of installation.
- Deeper hole depths possible.
- Rapid and remote monitoring possible.
- Immediate deformation determinations.
- Complex installations possible.

Recent advances have also been made in the use of TDR for monitoring ground water levels and piezometric pressures (Dowding, *et al.* 1996). A summary of applications of TDR in the mining industry is provided by O'Connor and Wade (1994).

Borehole Extensometers: An extensometer consists of tensioned rods anchored at different points in a borehole (figure 5). Changes in the distance between the anchor and the rod head provide the displacement information for the rock mass.

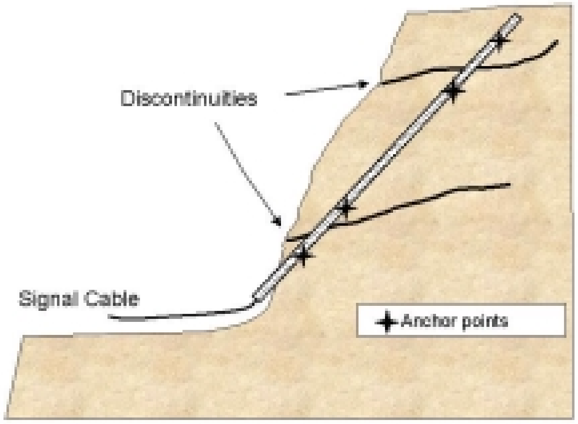

Figure 5. Multi-point borehole extensometer.

Piezometer: Piezometers are used to measure pore pressures and are valuable tools for evaluating the effectiveness of mine dewatering programs and the effects of seasonal variations. Excessive pore pressures, especially water infiltration at geologic boundaries, are responsible for many slope failures. Data on water pressure is essential for maintaining safe slopes since water behind a rock slope will decrease the resisting forces and will increase the driving forces on potentially unstable rock masses. Highwalls should be visually examined for new seeps or changes in flow rates as these are sometimes precursors to highwall failure. Additionally, pit slopes should be thoroughly examined for new zones of movement after heavy rains or snowmelts.

RESEARCH AND TECHNOLOGY

Stress, gravity loading, rock mass strength, geology, pore pressure, the presence of unknown underground workings, and many other factors contribute to slope failures. Because of the enormous surface area of many large open-pit mines, several varieties and scales of instabilities can occur. Complete vigilance to monitor each and every potential failure block is neither feasible, nor economical, and is certainly not attainable using today's most common point displacement monitoring techniques. Many of the current monitoring methods are also difficult to implement at quarries and surface coal mines, where near-vertical faces and lack of benching limit access to areas along the highwall. Additionally, as mining progresses, it is necessary to monitor different sections of the pit walls. Continually relocating devices is not only a costly and time consuming operation, but can also be dangerous -- especially with an unstable slope.

In an effort to make up for the shortcomings of point monitoring systems, NIOSH is examining new technology for slope monitoring that will look at the entire surface of the mine highwall for rock mass displacement and rock mass composition (Girard, 1998). Additionally, software has been created under a NIOSH contract to assist geotechnical engineers with bench designs to minimize rock fall hazards. A discussion of each technology follows.

Highwall Monitoring Using Radar Systems

Synthetic aperture radar (SAR) is a type of ground-mapping radar originally designed to be used from aircraft and satellites. SAR can be used to generate high quality digital elevation maps (DEM's) and to detect disturbances of the earth's surface. A variation of SAR – Interferometric Synthetic Aperture Radar (IFSAR) – uses differences in time-lapsed SAR images to generate maps of displacements (Fruneau and Achache, 1996). This technique has been successfully applied to produce displacement maps of ground movement caused by earthquakes, volcanic activity, and mine subsidence (Massonet, 1997; Canec, 1996). IFSAR can also be used to monitor displacement of unstable slopes or landslides (Reeves *et al*., 1997; Sabine *et al*., 1999).

IFSAR's have many advantages over current types of monitoring systems. Able to work in nearly all weather, an IFSAR can acquire imagery through fog, mist, rain, haze, or cloud cover, and can operate day or night. Also, an IFSAR can sample a large area for ground displacements, which gives them a tremendous advantage over survey networks, extensometers, and other instruments which sample movement on a discrete set of points. Recent developments in instruments such as prismless laser range finders partially address the problem of under sampling large areas for movement. However, the range and accuracy of these units can vary greatly depending on the reflectivity of the rock, the angle of the rock face, weather, and other factors. Manufacturers of prismless range finders generally claim a range of 500 meters or less.

The Microwave Earth Remote Sensing Laboratory at Brigham Young University (BYU) has recently designed and built a small synthetic aperture radar system capable of operating from light aircraft or from stationary ground-based stations (Thompson, 1998). The first field tests related to geohazards monitoring using this instrument were performed by BYU for the Canadian National Railways (CN). The railways were interested in finding a method to accurately detect rockfalls and washouts on railroad tracks before trains approached those dangerous areas. The initial results from those tests were positive, and BYU researchers are confident that their system can be adapted for NIOSH to monitor highwalls at mines. Field tests are anticipated to begin in the fall of 2000.

Imaging Spectroscopy

A contributing factor in many highwall failures is the presence of mechanically incompetent, argillically-altered rock. Major structures are generally well mapped, but weak rock units may be much more difficult to identify. Mine maps can vary greatly in quality and detail due to the subjectivity of various geologists and the extreme geologic complexity of many deposits. In addition, there are financial and practical limits to the number of samples that can be taken for geochemical or engineering analyses. Oftentimes, a large percentage of the data shown on geologic maps is an estimation by a geologist or mathematical interpolations of geotechnical results.

In order to help identify weak rock structures and remove ambiguity from geologic mapping, NIOSH researchers are testing applications of imaging spectrometers (Sabine, *et al*., 1999). An imaging spectrometer is a device that can determine the composition of minerals from a distance by analyzing the diagnostic spectral absorption signatures (unique reflectance patterns of light that uniquely define each mineral). Like IFSAR, imaging spectrometers have been used from satellites and aircraft for geologic mapping for quite some time, but recent advances in technology have led to the development of smaller, portable, units that can also work from ground level.

One such instrument has been developed by a team of researchers at Carnegie-Mellon Research Institute (Denes *et al*., 1997). The instrument (figure 6), known as a spectro-polarimetric imager (SPI), utilizes an acousto-optic tunable filter (AOTF) to detect the interaction of light and acoustic waves in certain crystals. The optical absorption or reflectance spectrum in the presence of ambient light then reveals the composition of objects in the image.

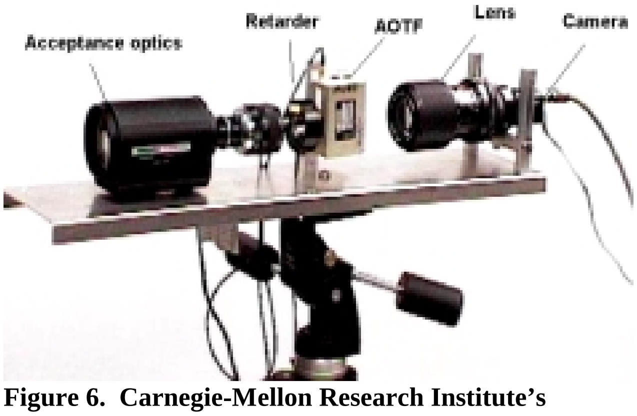

Figure 6. Carnegie-Mellon Research Institute's Spectro-polarimetric Imager.

In July 1999, NIOSH and Carnegie-Mellon Research Institute (CMRI) researchers conducted field-tests of the SPI for mine highwall imaging at Molycorp's Mountain Pass Mine near the

California/Nevada border. This particular mine site was selected for field tests because the diagnostic spectral signatures of the ore (lanthanide series rare earths) are within the current spectral range of the prototype instrument.

Multispectral images were collected at twelve scenes at the Mountain Pass mine, including pit highwalls, outcrops, drill core, and hand samples. Figure 7a shows an area of interest (approximately 30 x 40 ft) on an exposed highwall. After the images were collected, substantial image processing, filtering, and computer analyses were performed. Figure 7b shows the results of the image analyses. The light areas are ore and the darker areas are waste rock. The field tests were successful in that the SPI images clearly illustrate the capabilities of the instrument to collect a multispectral image and discriminate materials within the image that may or may not be distinguishable by the human eye.

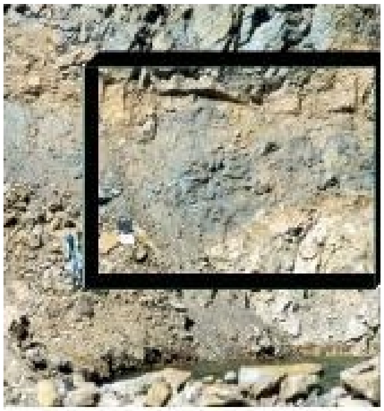

Figure 7a. Region of interest for field test of SPI.

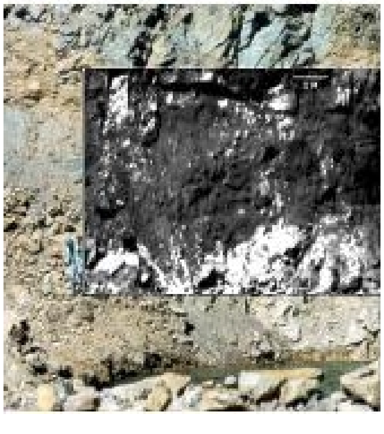

Figure 7b. Results of SPI image analyses. Light areas correspond to bastnaesite ore, darker areas waste or unclassified spectra.

There are many advantages to using spectral analyses for geologic mapping. First of all, spectral identification of minerals would remove the human error and subjectivity of trying to visually determine the degree of alteration in a rock mass. Secondly, workers would be able to map mine highwalls, or other inaccessible or unsafe areas, from a safe distance. However, this instrument will only be useful for imaging weak, altered zones in pit highwalls if the spectral range is extended further into the infrared region. At this time, funding for this advancement in technology is not available at NIOSH or at CMRI.

Bench Design Software

Thorough engineering analyses of large slope cut in discontinuous rock masses often include investigations of bench stability. If kinematically viable rock failure modes are present in benches, it is unlikely that actual bench widths will match the original slope geometry plan. Consequently, rock fall hazard assessment and related slope stability safety issues must consider the operational (“as-built”) catch-bench geometry and not the idealized (“as-designed”) geometry.

Minor bench instabilities and rock falls adversely impact mine safety in two key areas. First, as failures break back along the top of a bench, storage capacity for holding rock fall debris is significantly reduced and falling rock from above may not be caught and retained on the bench (see figure 8). Secondly, large amounts of rock fall debris on benches may even trigger multiple-bench failures. Therefore, the ability to predict the volumes of bench-scale failures is essential for properly designing wide enough catch benches.

In order to assist mine operators with bench design, computer software has been developed for NIOSH’s Spokane Research Laboratory (Miller, 2000). The software computes the probability of bench stability for plane shear or wedge failures using basic geological engineering input on bench dimensions, rock mass characteristics, and fracture data. After all of the potential failure geometries are computed, the probability of sliding is computed using a stochastic shear strength model (Miller, 1988; Miller and Girard, 2000.)

Results from a bench stability study can be used to help select inter-ramp slope angles and overall slope angles. Bench geometry has a direct influence on the overall slope angle as expressed by:

$$\tan(A)=1/[(W/H) + (1/\tan B)] \qquad (1)$$

Where: A = overall (average) slope angle;
B = bench face angle
H = vertical height of bench; and
W = horizontal width of bench.

Using this relationship and output from the software, geotechnical engineers can design overall slope angles and bench configurations to minimize extensive loss of catch bench width and thus minimize rockfall hazards.

Figure 8. Small, unexpected rock falls may indeed be more hazardous than a massive failures that involve slow displacement of material over a longer period of time.

CONCLUSIONS AND RECOMMENDATIONS

Steps need to be taken to reduce the number of mining deaths resulting from slope instability. Diligent monitoring and safe design by qualified geotechnical engineers at mine sites is crucial. Additionally, proper catch bench design, blasting patterns that minimize overbreak, effective highwall scaling (where appropriate), and dewatering of potentially unstable zone are also important to minimize hazards related to highwall failures.

There are many new technologies being explored, but remote sensing, at the present time, cannot replace conventional geotechnical methods of investigation. A great deal of research is still needed to design and test new systems in order to make certain they are scientifically valid and economically viable options.

The NIOSH Slope Stability Hazard Recognition Team is pursuing a variety of research options to minimize the dangers associated with surface ground control problems. Results of this research may also benefit others involved in studies of landslides, rock falls, avalanches, volcanic activity, and other geohazards.

For more information about this or any other NIOSH project call 1-800-35-NIOSH. Or visit the website at: http://www.cdc.gov/niosh

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