Advances in Remote Sensing Techniques for Monitoring Rock Falls and Slope Failures

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ABSTRACT

Ground control problems at surface mining operations can occur for a variety of reasons. Stress, gravity loading, rock strength, geology, pore pressure, weather effects, underground workings, and many other factors contribute to slope instabilities that range from small rock falls to massive slides of material. While some of these failures can be predicted or controlled by preventive measures, each year many completely unexpected failures occur. Current methods for monitoring generally involve measuring displacements at a few, selected points in and around the suspected area of instability. While most of the displacements along these points will be in a downslope direction, freeze-thaw cycles of water-filled joints, horizontal stresses or pressure, buoyancy in saturated soils, human measurement errors, or other situations can produce deformation in almost any direction, even without any instability in the slope. Determination of which, if any of the observed movements represents a potential hazard is essential.

Because of the enormous surface area of many large open-pit mines, several varieties and scales of instability can occur. Small, unexpected rock falls may indeed be more hazardous than a massive failure that involves slow displacement of material over a longer period of time. Complete vigilance to detect all small potential falling blocks is neither feasible nor economical and certainly is not attainable using today's most common point displacement monitoring techniques. As part of an on-going study at the Spokane Research Laboratory, several new methods for monitoring slope instabilities are being investigated. This paper describes the potential adaptation of systems such as interferometric synthetic aperture radar, imaging spectroscopy, and time-domain reflectometry, to slope monitoring and design.

INTRODUCTION

In February 1997, the Spokane Research Laboratory, of the Office for Mine Safety and Health Research, initiated a research program with the goal of reducing the number of injuries and fatalities resulting from slope failures at mines. To distinguish the number of incidents associated with slope failures, Mine Safety and Health Administration (MSHA) narratives of 1,293 fatal accident investigations from 1978 to 1997 were reviewed. The results of this data analysis showed that 85 deaths (approximately 6.6% of all surface mine fatalities) were attributable to surface ground control problems. Each year since 1978, at least one, and as many as 11 miners, have been killed in slope failure accidents.

While MSHA fatality data is useful in approximating the danger level associated with slope instability, actual risks from surface ground control problems are much higher than the statistics indicate. Many falls of ground at surface mines do not injure mine personnel or significantly affect operations; such incidents are seldom reported. Also, the MSHA classification codes can lead to ambiguity when trying to define which accidents are directly attributable to a slope failure. As an example, a haul truck could back up to a dump and go over the edge. Such an incident would be classified as a "powered haulage" accident. However, the truck may have gone over the edge because the berm was not adequate, because of operator error, because the rock slope failed, or a combination of factors. An MSHA report of surface powered haulage accidents (Fesak, et al., 1997) states, "Between January 1990, and July 1996, 136 trucks and other haulage vehicles overturned while dumping material at edges of dump locations. This type of accident occurred more frequently than any other." In addition, the report goes on to say, "Most frequently, the haulage vehicle backed onto unstable fill material that gave way..."

These analyses of fatality data indicated that surface mine ground control problems are directly responsible for a significant number of fatalities, and steps are needed to minimize hazards to workers. There are several means to minimize the chances of surface ground control failures: 1) safe geotechnical designs; 2) secondary support systems or rock fall catchment systems; or 3) systems for advance warning of impending failures. However,

Figure 1 -- Massive slope failure in the highwall of an open pit mine.

while geotechnical designs can be improved to increase factor of safety, and support systems can enhance the overall rock mass strength, even a carefully designed slope may be subject to instability. The objective of this paper is to briefly introduce the most common slope monitoring systems currently in use, describe the limitations of these systems, and present new remote sensing technologies that may be applicable to advanced monitoring and design of dumps, highwalls, tailings dams, and other slopes.

CONSEQUENCES OF SLOPE FAILURES

At any open pit mine, some degree of slope instability should be expected. Ground control problems at surface mining operations occur for a variety of reasons and instabilities can range from small rock falls to massive slides of material. Figure 1 shows a massive slope failure in the highwall of an open pit mine. While some failures can be predicted or controlled by preventive measures, each year many completely unexpected failures occur which result in fatalities, loss of equipment, significant changes to mining plans, and extreme costs to mining companies. Figure 2 shows a close-up of the devastating results of a much smaller, but unexpected, slope failure.

Open pit slopes are generally designed to a minimum acceptable safety factor. However, variability in rock strengths, hidden geologic structures, underground workings, gravity loading, pore pressure effects, and many other factors can cause instability even in a "safe" slope. The fact that a slope is designed with some risk of failure must not be viewed as a disregard for safety. As long as the risks are known, and a sufficient, suitable monitoring system is provided, remedial engineering and safety measures can be taken (Call and Savely, 1990).

Figure 2 -- Unexpected slope failures endanger lives and demolish equipment.

TYPICAL SLOPE MONITORING SYSTEMS

Displacement measurements are the most common type of monitoring, complemented by monitoring of groundwater pressure. The objectives of a slope monitoring program are 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 brief summary of the *most common* monitoring systems currently in use and is not intended to be an all-inclusive list of monitoring equipment.

Surface Measurements

Survey Network: A survey network consists of target prisms placed on and around areas of anticipated instability on the pit slopes) and one or more control points for survey stations. These stations need to be located close enough to the pit crest so that all prisms can be seen, and must be located on completely stable ground. 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. Dust, haze, human error, damaged prisms, or displacement of the survey station can affect measurement accuracy.

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 propagation is required to establish the extent of the unstable area. Measurements can be as simple as driving two stakes on either side of the crack and using a survey tape or rod to measure the separation. One problem with monitoring cracks at the crest of a slope is that the movement has already occurred. Additional cracking will potentially weaken the entire area making the ground loose and measurements inaccurate. Existing cracks should be painted or flagged so that new cracks are easily detected on subsequent inspections. Further movement may also introduce safety concerns or limit access to the area. In an unstable area, care should be taken to quantify the failure mode and monitor the instability as a whole. Tension crack mapping at the crest is oftentimes not indicative of the extent or seriousness of the potential failure.

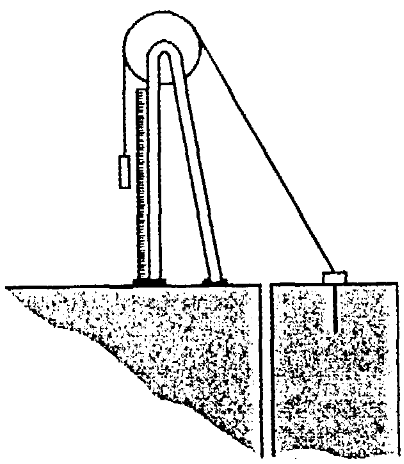

Figure 3 -- Wire extensometer

Wire Extensometers: Wire extensometers are simple systems that can be used to monitor areas of active instability. A common setup (figure 3) is comprised of a wire anchored in the unstable portion. The wire runs over the top of a pulley and has a weight suspended from the other end. As the unstable portion moves away from the pulley stand the weight will move, and the displacements can be recorded. The length of the extensometer wire should be limited to approximately 60 m (197 ft) because sag can produce inaccurate readings (Call and Savely, 1990). The weight of the wire used will also determine the amount of counterweight needed. Some wire extensometers are fitted with warning signals which are activated when a significant amount of displacement occurs. These signals were removed by mine personnel at one particular site visited by NIOSH researchers because birds kept landing on the wires and setting off false alarms.

Subsurface Measurements

Inclinometers: An inclinometer consists of a casing that is placed in the ground through the area of expected movements. The end of the casing is assumed 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. 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 installation. Inclinometers are relatively expensive and are not well suited to routine monitoring.

Extensometers: An extensometer consists of tensioned rods anchored at different points in a borehole. Changes in the distance between the anchor and rod head provide the displacement information for the rock mass. Extensometers are most suited to measuring deformation behind retaining structures. Since conventional extensometers only measure deformation parallel to the borehole, they are of less benefit in slope applications than inclinometers which measure deformation normal to the borehole.

Piezometer: Piezometer are used to measure pore pressures and are valuable tools for monitoring the effectiveness of mine dewatering programs. Excessive pore pressures, especially water infiltration at geologic boundaries, are responsible for many slope failures. Data on water pressures is essential for maintaining safe slopes.

REMOTE MONITORING TECHNOLOGIES

Synthetic Aperture Radar

Synthetic aperture radar (SAR) is a type of ground-mapping radar originally designed to be used from aircraft and satellites. Exploration geologists have benefited from SAR imagery since the 1970's (Rossignol and Corbley, 1996). SAR can be used to generate terrain maps, to produce high quality digital elevation models (DEM's), and to detect surface disturbances or changes in surface moisture. SAR instrumentation that works from a ground level has been developed recently.

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 and volcanic activity (Massonet, 1997). Figure 4 is an example of a displacement map generated as a result of the 1992 Landers earthquake. The interference fringes indicate displacements.

IFSAR has also been used to measure sea ice movement in Antarctica (Goldstein et al., 1993), model ocean wave patterns,

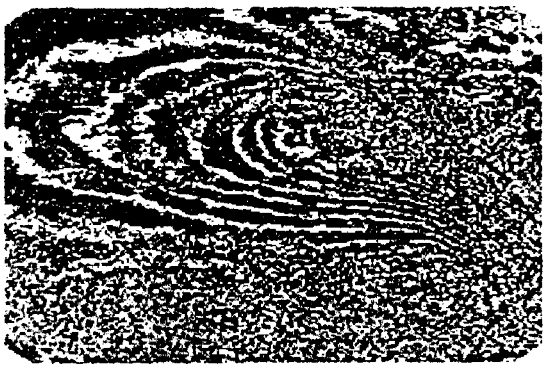

Figure 4 -- Interferogram of earth displacements along a fault.

monitor and map clear-cut or fire damage to forests, map the extent of flood damage and produce hydrologic models. IFSAR can also be used to monitor displacement of unstable slopes or landslides.

IFSAR's have many advantages over current types of monitoring systems. Able to work in nearly all weather, IFSAR can acquire imagery through fog, mist, rain, haze, or cloud cover, and can operate day or night. Also, they sample a large area for ground displacement which gives them a tremendous advantage over survey networks, surface extensometers and other instruments that sample movement only at a few, select points. Recent developments in instruments such as prismless laser range finders partially address the problem of undersampling 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.

For the purpose of slope monitoring at mines, IFSAR could be used to produce displacement maps of the *entire* highwall. In addition, information could be obtained on soil moisture content and the effects of dewatering could be tracked. Volume estimations from IFSAR-generated DEM's could be used for production purposes, and information obtained on the delineations of geologic structures would provide input for design purposes and possibly even ore control.

Imaging Spectrometry

In addition to displacement monitoring, information on geologic structures and weak rock units that have the potential for causing slope instabilities need to be incorporated in the monitoring program. An imaging spectrometer is a device that can determine the composition of rocks from a distance by their spectral signature. Like IFSAR, imaging spectrometers have been used from satellites and aircraft for geologic mapping, but recent advances in technology have led to the development of smaller units that can also work from a ground level. Spectrometers can also be used for such diverse applications as monitoring pollution or hazardous waste spills and monitoring the health of replanted vegetation. Some simple spectrometers are already being used in the mining industry to log drill core, identify rock in outcrops or exposed faces, and for petrographic analyses in the laboratory.

The need for geologic mapping of mine areas needs to be improved. The design of mine slopes, the placement of waste dumps, tailings dams, mine roads, etc. is based on geologic maps that show the location, attitude, and character of geologic structures and ore-bearing rock units. However, 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 geotechnical samples that can be taken for analysis and engineering purposes, so much of the data shown on geologic maps is an estimation by a geologist or a mathematical interpolation of geotechnical results. Figure 5 is a spectrometer image clearly delineating fault areas, folds, and numerous rock types.

Figure 5 -- Spectrometer image.

For the purposes of slope stability, hydrothermally-altered rocks, large faults or other geologic structures can be responsible for slope instability. Major features are generally well-mapped, but weak rock units may be much more difficult to identify. Imaging spectrometry provides a means of mapping highwall or other surface geology, without the subjectivity of varying geologists interpretations. The information on geology couple with IFSAR information on displacements could identify rock units responsible for causing instability. Recognition of similar situations encountered as mining progressed could be accounted for before instability occurred.

Time Domain Reflectometry

Time Domain Reflectometry (TDR) is a technique in which electronic pulses are sent down a length of a coaxial cable. When a deformation or a break in the cable is encountered, a signal is reflected. Early research on TDR began in the early 1960's to locate breaks in electrical power cables (Moffit, 1964). Panek and Tesch (1981) and O'Connor and Dowding (1984) were among the first to use TDR to measure rock mass deformation.

Inclinometers are currently the most common method of monitoring subsurface deformation in unstable slopes. However, TDR cables are rapidly increasing in popularity and have many advantages over traditional inclinometers (Kane, 1998) as follows:

- **Lower cost of installation.** Cables cost 2% to 38% less than inclinometer casing.
- **Deeper hole depths possible.** Inclinometers in deep hole require special winches and cables due the extreme weight of the equipment. All TDR monitoring equipment is at the surface.
- **Rapid and remote monitoring possible.** TDR data can be transmitted via telecommunications (Campbell Scientific Inc., 1998), and scanning and recording intervals can be programmed remotely to examine zones of interest.
- **Immediate deformation determinations.** Locations of any movement are determined immediately using TDR. Additional data reduction is generally not necessary, and the cables can be used to quantify rock movement as well as distinguish shear and tension (Dowding, et al., 1989).
- **Complex monitoring situations.** TDR cables have been installed in angled boreholes, and have monitored deep zones below moving upper zones. Neither installation could have been done with a traditional inclinometer.

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).

CONCLUSIONS

Remote sensing, at the present time, cannot replace conventional geotechnical methods of investigation, but emerging technologies should not be ignored. Interferometric synthetic aperture radar, imaging spectrometry, and time domain reflectometry are already widely used to monitor hazards such as landslides, volcanoes, and active faults. As computer processing speeds increase and technology continues to advance, integration of remote sensing into mine operations can improve slope design and reliability of slope monitoring.

Our research team is interested in exploring the benefits of using multiple remote sensing methods to better understand slope failures. IFSAR coupled with an imaging spectrometer will provide detailed geologic and topographic maps and will detect and monitor hazardous earth movements, day or night, in nearly all weather, along the entire slope surface. Field tests of imaging spectrometry and interferometric radar are scheduled for two copper mining operations this summer. Results of the field tests will be available from the authors early in 1999.

Steps need to be taken to reduce the number of mining deaths resulting from slope instability. Advancement of monitoring and early warning systems is merely one option. The Slope Stability Hazard Recognition Team at Spokane Research Laboratory is pursuing many other research options to minimize the dangers associated with surface ground control problems. Results of this research will benefit others involved in the study of landslides, rock falls, avalanches, volcanic activity, and other geohazards.

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