ASSESSING AND MONITORING OPEN PIT MINE HIGHWALLS

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INTRODUCTION

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 and other unexpected failures of ground. The purpose of this paper is to introduce various warning signs of slope instability so operators are better able to recognize hazards. The most common slope monitoring equipment and practical methods of installation are discussed as well as the limitations of these systems.

CONSEQUENCES OF SLOPE FAILURES

Unexpected movement of ground causes the potential to endanger lives, demolish equipment, or destroy property. Between 1995 and 2001 (2nd quarter), 34 fatalities were caused by ground instability. This accounts for approximately 15% of all surface mine fatalities (Figure 1). These figures include fatalities classified by the Mine Safety and Health Administration (MSHA) as "fall of face or highwall," "powered haulage," "equipment," and other MSHA accident categories, where the primary cause of the accident was unanticipated movement of the ground. This includes fatalities resulting from bench and highwall failures, rock falls, waste dump and stockpile failures, and the collapse of unknown underground workings.

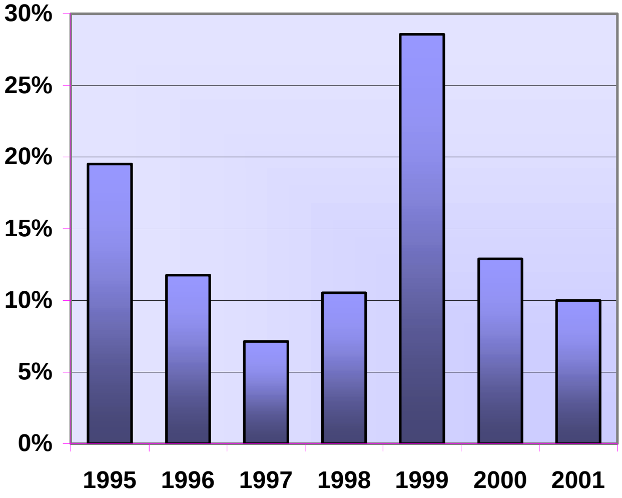


Figure 1. Percentage of surface mine fatalities that were caused by unstable ground conditions. 1999 was the highest year in this period with 28%. (NOTE: 2001 data is only current thru July.)

The fatalities occur most often at stone mines followed by coal, sand & gravel, and metal operations. As can be seen in figure 2, the problem is pervasive in all four commodities. Due to the significance of the problem, NIOSH's Spokane Research Laboratory maintains a research program dedicated to reducing the number of injuries and fatalities resulting from ground instability at surface mines.

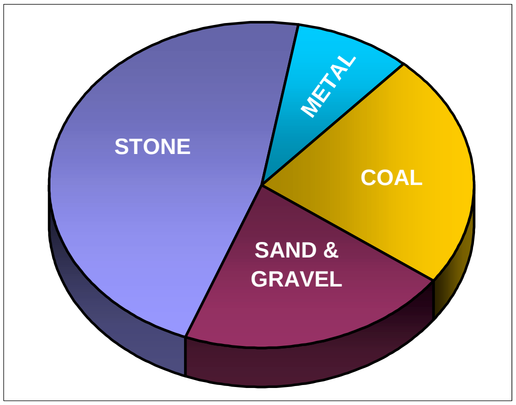


Figure 2. Percent distribution of 34 fatalities from 1995 through the 2nd quarter of 2001 at surface operations (grouped by commodity).

There are several ways to reduce the hazards associated with slope failures: 1) safe geotechnical designs; 2) secondary supports or rock fall catchment systems; 3) monitoring devices for adequate advance warning of impending failures; and 4) proper and sufficient scaling of loose/dangerous material from highwalls. At any surface operation, some instability can be expected – from minor bench raveling to massive slope failures (Figs. 3 & 4).

(source: Wharf Resources, South Dakota)

Figure 3. Minor raveling along a bench face

(source: Twin Creeks Mine, Nevada)

Figure 4. Massive slope failure at an open pit gold mine did not cause any injuries or accidents, but did cause significant production problems and high costs.

Diligent monitoring and examination of slopes for warning signs is imperative for protecting workers and equipment. Geotechnical designs can be improved to increase factors of safety and proper bench designs can be improved to minimize rock fall hazards. However, even slopes with conservative slope designs may experience unexpected failure due to the presence of unknown geologic structures, abnormal weather patterns, or seismic shock. Unanticipated movement of any amount of rock may cause severe disruptions to mining operations, pose major safety concerns, or contribute to large financial losses for companies (Figure 5).

(source: Mine Safety & Health Administration, 2000)

Figure 5. Fatality and loss of equipment caused by unexpected slope failure.

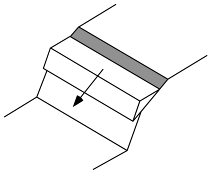
Even the smallest of failures can be problematic if benches fail that support main haul roads, or if facilities are threatened by displacement of the rock mass. Failure to adequately scale highwalls at quarries can also have devastating consequences as can be seen from the excerpts of these recent MSHA fatal accident investigation reports:

> *"a rock found near the victim…measured about 4 by 4 by 3 inches and weighed 2 pounds, 13 ounces"* (MSHA, 1999a)
>
> *"A rock fell from the quarry wall striking the victim, causing fatal injuries. … Death was attributed to head trauma. … The rock or rocks that struck the victim could not be identified, nor could it be determined from what height they fell from the highwall."* (MSHA, 1999b)

DETERMINATION OF POTENTIAL FAILURE GEOMETRY

To determine which failure modes are possible at a particular operation the geologic parameters in various sectors of the mine need to be quantified. Collecting information such as orientation, spacing, trace length, and shear strength with respect to major structures and other geologic features is an important key to determining failure potential. The basic failure modes which may occur are:

Plane Failure: Plane failures occur when a geologic discontinuity, such as a bedding plane, strikes parallel to the slope face and dips into the excavation at an angle steeper than the angle of friction.



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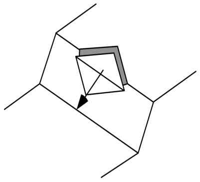
Wedge Failure: Wedge failures occur when two discontinuities intersect and their line of intersection daylights in the face.



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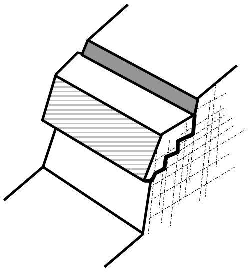
Step-path Failure: Step path failure is similar to plane shear failure, but the sliding is due to the combined mechanisms of multiple discontinuities or the tensile failure of the intact rock connecting members of the master joint set.



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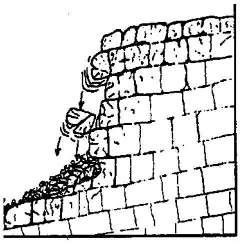
Raveling: Weathering of material and expansion and contraction associated with freeze-thaw cycles are principle causes of raveling. This type of failure generally produces small rockfalls, not massive failures.



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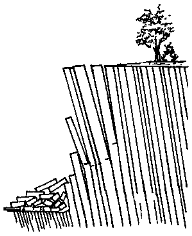
Toppling Failure: Toppling can occur when vertical or near-vertical structures dip toward the pit. If this type of structure is present, the bench face height should be limited to a distance approximately equal to the bench width. This will help catch any toppling material and decrease the chances of impacting equipment working on the pit floor below.



[Note: *Several other complex failure modes are possible or have been proposed by others. The reader is referred to Sjoberg, 1996 for descriptions and literature reviews, but it is not within the scope of this paper to describe all of these in great detail.*]

* * *

The first step in determining whether these basic failure modes are present is to thoroughly map the geology (descriptions of data collection methods are found in Piteau, 1970; Call, et al., 1976; Miller, 1983; Nicholas and Sims, 2001). By plotting the orientation of the discontinuities and the cut face of the slope on a stereonet, potential slope stability problems can be recognized. Graphical representations of the data are also useful for eliminating structures which are unlikely to cause slope stability problems. (Readers are referred to Hoek & Bray, 1981; Panet, 1969; and John, 1969 for the background and methodology.)

RECOGNIZING HAZARDS

As previously mentioned, even the most carefully designed slopes may be subject to instability. Acknowledging that slope failures may occur and knowing what the warning signs are will contribute to the safety of the operation. Some of the more common warning signs of slope instability follow:

Tension Cracks :

The formation of cracks at the top of a slope is an obvious sign of instability (figure 6). Cracks form when slope material has moved toward the pit. Since this displacement cannot be detected from the pit floor, it is extremely important to frequently inspect the crests of highwalls above active work sites. Safe access should be maintained at all times to the regions immediately above the active mining. Frequent inspections may be necessary during periods of heavy precipitation or spring run-off and after large blasts.

Figure 6. Example of tension cracks.

Scarps:

Scarps (figure 7) occur where material has moved down in a vertical or nearly vertical fashion. Both the material that has moved vertically and the face of the scarp may be unstable and should be monitored accordingly.

Figure 7. Example of a scarp

Abnormal Water flows:

Sudden changes in precipitation levels or water flow may also precede slope failures. Figure 8 illustrates a saturated plane in a failing slope.

Figure 8. Seep in failing slope.

Spring run-off from snow melt is one of the most obvious examples of increased water flow that may have adverse affects on slopes. However, changes in steady flow from dewatering wells or unexplained changes in piezometer readings may also indicate subsurface movement that has cut through a perched water table or intersected a water bearing structure. Changes in water pressure resulting from the blockage of drain channels can also trigger slope failures. Water can also penetrate fractures and accelerate weathering processes. Freeze-thaw cycles cause expansion of water filled joints and loosen highwall material. Increased scaling may be necessary during cold weather.

Bulges or Creep:

Bulging material or "cattle tracks" appearing on a slope indicate creep or slow subsurface movement of the slope. Other indicators of creep can be determined by looking at vegetation in the area (Figure 9). While most mines do not have vegetation on the slope faces, movement of trees at the crest of a slope can be an indicator of instability.

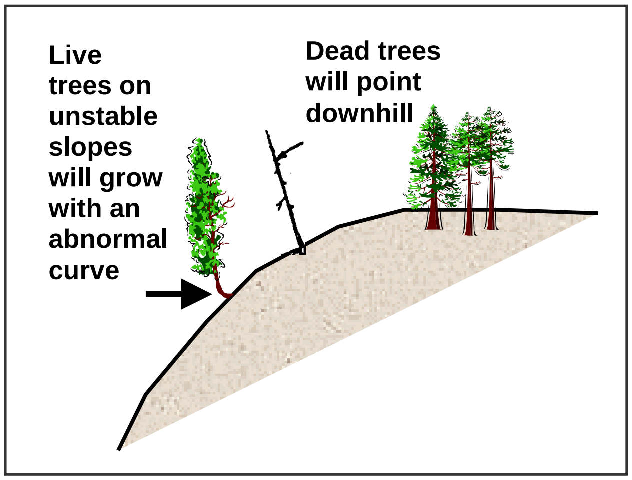


Figure 9. Other potential signs of instability

Rubble at the Toe:

Fresh rubble at the toe or on the pit floor is a very obvious indicator that instability has occurred. An effort must be made to determine which portion of the slope failed, and whether more material may fail. One of the most dangerous situations that can occur is an overhang. If workers are not aware that a portion of the material below them has failed, they may unwittingly venture out onto an unsupported ledge (Figure 10.)

Remedial measures such as scaling, supporting, or blasting the overhang or other hazardous rock may be necessary (Figure 11).

Figure 10. The overhang indicated by the arrow is a hazard to trucks traveling along the haul road because the drivers cannot see the portion of the slope that has failed below the road. The weight of the trucks on the partially failed material could cause the rest of the rock mass to fail.

Figure 11. A worker suspended by mountain climbing gear is supporting a potentially unstable overhang with cable bolts.

MONITORING EQUIPMENT

The type of instruments selected for a slope monitoring program depends on the particular problems to be monitored. A comprehensive monitoring system may include instruments capable of measuring rock mass displacement, ground water parameters, and blast vibration levels. Excellent overviews of equipment and specification exists in CANMET, 1977; and

Szwedzicki, 1993. Some of the most common monitoring equipment is profiled below. (For information on blast vibration monitoring and damage control techniques see Hustrulid, 1999; Oriard, 1972; Scott, 1996; and, Cunningham, 2001.)

Survey Network:

The use of EDM (electronic distance measurement) equipment is a very common and effective method for monitoring slopes. The survey network consists of target prisms placed on and around areas of anticipated instability 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. The surveys can be done manually by a survey crew or can be automated.

Manufacturers generally publish the accuracy and error limits of their equipment. Index of refraction errors may occur as a result of atmospheric variations in temperature or pressure, and human error can be a factor with manual systems. Surveying instruments need to be carefully adjusted and correctly calibrated according to manufacturers' instructions to ensure equipment accuracy and reliability. It is extremely important that permanent control points for the survey stations are placed on stable ground and that the target prisms are securely anchored. Errors can cause a serious discrepancy in data, and steps need to be taken to ensure these errors remain negligible. The source of all errors for the surveying method must be less than the minimum required accuracy of the displacement measurements.

Tapes, Crack Meters, Pins, etc.

Measuring and monitoring the changes in crack width and direction of crack propagation is required to establish the extent of the unstable area. The simplest method for monitoring tension cracks is to spray paint or flag the ends so that new cracks or propagation along existing cracks can be easily identified on subsequent inspections. Measurements of tension cracks may also be as simple as driving two stakes on either side of the crack and using a survey tape or rod to measure the separations.

Stakes can become loose over time and cause inaccurate measurements. Multiple stakes can be installed to help maintain some reliability in measurements. Commercial crack gages with electrical readout are also available, but often in the case of mine slope problems, the cracks exceed the measurement limits of the instruments.

No matter what method is selected for measuring crack displacement, the devices should be marked with the dates of installation and show the magnitude and direction of movement. Monitoring at regular intervals is important. Care should be taken to keep personnel off the unstable portion of the slide when installing . equipment or taking readings.

Wireline Extensometers:

Another common method for monitoring movement across tension cracks is with a portable wire-line extensometer (Fig. 12). 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. Electronic monitoring equipment can be programmed to set off alarms if the displacement reaches certain threshold limits.

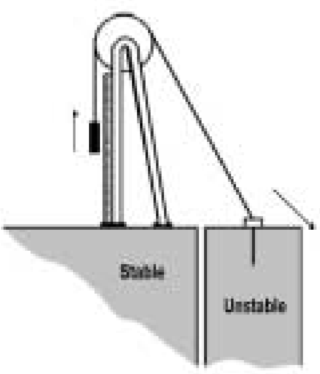


Figure 12.

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). Long lengths of wire can lead to errors due to sag so readjustments and corrections are often necessary. Some extensometers are sensitive to movements of 1 mm so simultaneous temperature readings should be taken to adjust for thermal expansion of the wire. Also, while it may sound foolish, birds often land on the wires of extensometers. This can contribute to a large number of false alarms and wildly inaccurate readings. Provisions for keeping wildlife away from the instrumentation should be made at operations where this may be an issue.

Inclinometers:

An inclinometer (Figure 13) 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. 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. Information collected from inclinometers can be used to (Kliche, 1999):

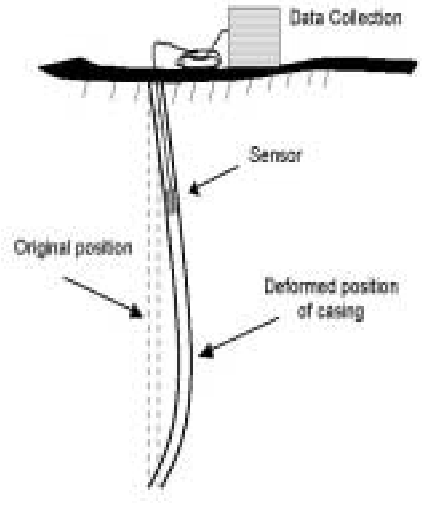


Figure 13. Cross-sectional schematic of typical traverse-probe inclinometer system. (adapted from Abramson, et al., 1996.)

- Locate shear zones.
- Determine whether shearing is planar or rotational.
- Determine whether movement along a shear zone is constant, accelerating, or decelerating.

Figure 14 illustrates the proper placement for inclinometers to monitor both shallow and deep-seated failure planes. If the bottom of the inclinometer is not in stable ground, the instrument may "float" in the failure zone and give erroneous readings. Excessive horizontal movement may deflect the casing so much that the sensing torpedo will not be able to pass the bend to take readings. Manufacturers will provide tables of instrument accuracy. CANMET (1977) recommends the use of small diameter, highly sensitive (1:10,000) inclinometers in rock slopes. If taking manual readings, two measurements (with the probe

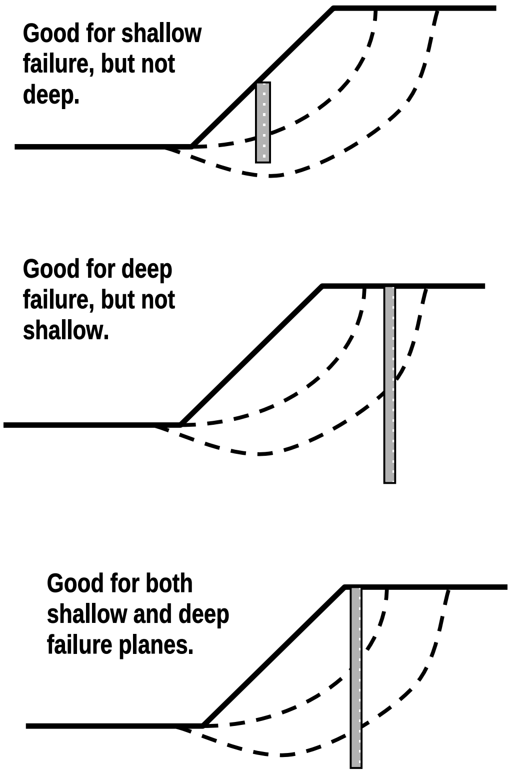


Figure 14. Proper inclinometer placement in a slope (adapted from Abramson et al., 1996)

rotated 180 degrees between measurements) should be taken to reduce errors.

Time Domain Reflectometry (TDR):

Time Domain Reflectometry is a technique in which electronic pulses are sent down a length of a coaxial cable which has been grouted in a drillhole. 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 Dowding (1984).

Piezometers:

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.

Borehole Extensometers:

A tensioned rod extensometer is used to detect and monitor changes in distance between one or more anchors in a borehole and the borehole collar (figure 15). Changes in the distance between the anchor and the rod head provide the displacement information for the rock mass.

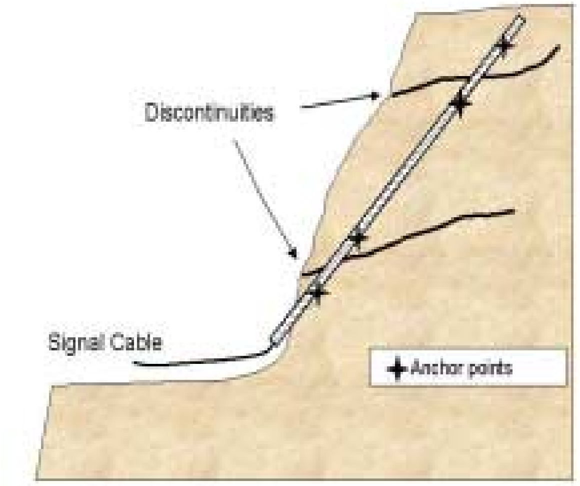


Figure 15. Multi-point borehole extensometer.

Extensometers of this type are best used to monitor known structural features which will have a major influence on slope stability. These instruments are fairly expensive when compared to other instrumentation options, and are therefore, not suitable for surveillance of large areas of the pit.

IMPLEMENTING A MONITORING PLAN

Sufficient, suitable monitoring must be provided to detect instability at an early, non-critical stage to allow for the initiation of safety measures. Monitoring "after the fact" does little to undo the damage caused by unexpected failures. Determining the objective of a monitoring plan is a seemingly simple, but crucial step in the instrumentation process. The purpose of a monitoring plan (adapted from Call & Savely, 1990) is to:

- Maintain safe operational practices for the protection of personnel, equipment, and facilities.
- Provide warning of instability so action can be taken to minimize the impact of slope displacement.
- Provide crucial geotechnical information to analyze the slope failure mechanism and design the appropriate corrective measures.

The following steps should be taken when planning the instrumentation portion of the monitoring program:

1. Understand the mechanisms that may cause instability.
2. Define and prioritize the geotechnical information required.
3. Establish monitoring locations.
4. Predict the magnitudes of movement and other parameters at these locations.
5. Establish an instrumentation budget.
6. Select instrumentation based on steps 1-5 above.

When selecting instrumentation, incorporate some level of redundancy in the system to cross-check instrument performance and eliminate errors. Redundant or over-lapping measurements will also provide a back-up in the case of instrument failure. Automated equipment is generally more accurate than manual equipment since some "human" error is removed. Automated systems also provide added flexibility in the sampling rate, and therefore can monitor more frequently than manual readings. Another distinct advantage of the automated systems is their ability to trigger alarms if certain threshold limits are reached. However, these systems are generally more expensive than manual systems, and the electronics may be more sensitive.

Other items to keep in mind when selecting equipment is the amount of personnel training that is needed and the time requirements for data collection. Personnel may require highly technical training to calibrate and maintain complex electronic systems. Sometimes installing a greater number of cheaper, reliable instruments is more useful than installing a few expensive, highly sensitive instruments. Instruments should be placed where they will be the most effective. Estimating the movement expected in a particular area should help ensure that the limits of the instrument are not exceeded. There may also be environmental limitations (extreme heat or cold, etc.) that determine whether a particular instrument will work at an operation. All of these factors need to be evaluated against the primary objectives of the monitoring program.

DATA REDUCTION & ANALYSIS

All slopes will deform in response to mining. The deformation will vary depending on the slope geometry, the geology, the rockmass properties, and the ground water conditions. Monitoring instruments are useful for collecting a large amount of data, but knowing what data is pertinent is will guide the necessary course of action.

Measure simple, obvious movements first -- surface displacements are very useful for determining the mechanism responsible for the instability and the extent of the failure surface. Plotting the rate of movement is the most important variable to track. If the rate of movement decreases, the slope may have temporarily stabilized. If the rate of movement increases, slope failure may be pending and more frequent readings of the site should be taken.

SLOPE STABILIZATION METHODS & PRE-PLANNED RESPONSE TO MOVEMENT

Even with diligent geologic mapping, careful geotechnical designs, and adequate monitoring programs, the chances for instability still exist. With today's instruments it is neither feasible nor practical to monitor every possible failure at an open pit mine. If material does fail, the mine should have a pre-planned response to the movement. If a slope failure is eminent, personnel must immediately be pulled out of the hazardous area. Operating procedures should be in place to establish what the threshold values of movement are, and how an evacuation scenario would be communicated to the workers. Standard operating procedures should also define those employees responsible for doing pre-shift inspections of highwalls, and define which personnel are responsible for collecting and compiling data from the monitoring instruments. Slope failures very rarely occur without some warning, and all workers need to be able to recognize potential hazards and act accordingly.

If the failure is not immediately threatening to personnel, a variety of other actions can be taken in response to the movement. The selection of remedial measures taken depends on the nature of the instability and the operational impact. Each case should be evaluated individually with respect to safety, mine plans, and cost-benefit analyses.

Let the material fail.

If the failure is in a non-critical area of the pit, the easiest response may be to leave the material in place. Mining can continue at a controlled rate if the velocity of the failure is low and predictable and the mechanism of the failure is well understood. However, if there is any question about the subsequent stability, an effort should be made to remove the material. Large-scale failures can be difficult and costly to clean up. Often, a mining company will choose to leave a step-out in the mine design to contain the failed material and continue mining beneath the step-out. The value of the ore that is lost needs to be evaluated against the costs of clean-up to determine if this is a feasible solution. The size of the blasts may also need to be reduced to minimize impacts on the unstable zone.

To prevent small-scale failures from reaching the bottom of the pit, both the number of catch benches and the width of catch benches can be increased. Catch fences (figure 16) have also been installed at some operations to contain falling material.

Figure 16. Catch fence installed to prevent loose rocks from traveling to the pit floor.

Support the material:

If allowing the instability to fail is not an option, artificially supporting the failure may be a solution. Some operations have successfully used reinforcement such as bolts, cables, mesh, and shotcrete to support the rock mass. The use of such supports can be very expensive. However if the overall angle of the highwall can be steepened and clean-up costs are reduced, the added expense of reinforcement may be justified. A careful study of the geologic structures must be performed to select the proper reinforcement (i.e. length of bolts or cables, thickness of shotcrete, etc.) Bolts that are too short will do little to prevent slope stability problems from continuing. In some cases, reinforcement has only served to tie several small failures together, creating a larger failure.

Another potential solution to stop or slow down a slope failure is to build a buttress at the toe. The buttress offsets or counters the driving forces of the slope by increasing the resisting force. Short hauls of waste-rock often make this an attrative and economical alternative for stabilizing slope failures.

Remove the hazard:

If a slope continues to fail, and supporting the slope is not a feasible alternative, steps need to be taken to remove the hazard. Often, flattening the slope to a more favorable angle with respect to the local geology will solve the problem (Fig. 17). When catchment systems are not available, proper and sufficient scaling methods should be employed on a regular basis to remove hazards associated with small rock falls.

Removing, or unweighting, the top portion of a slide may also decrease the driving forces and stabilize the area. However, Call & Savely (1990) warn that this option is generally "unsuccessful" and cite situations involving high water pressure where unloading actually *decreased* the stability of the remaining material.

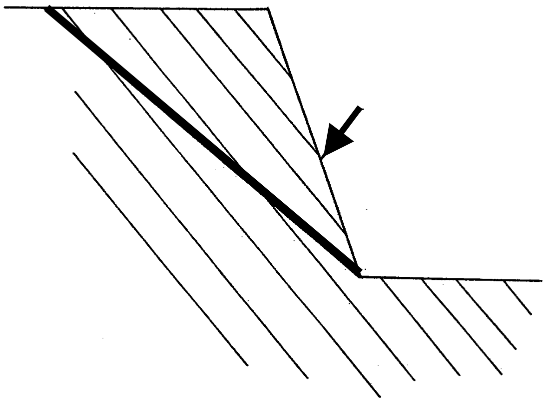


Figure 17. Flattening slope to avoid slope failures.

Since water pressure creates slope stability problems, dewatering using horizontal or vertical wells is a powerful means of controlling slope behavior and minimizing hazards. Surface drainage and diversions should also be used to keep surface runoff away from tension cracks and open rock mass discontinuities near the slope face.

FUTURE MONITORING TECHNOLOGIES

Because of the enormous surface area of many 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 steep highwalls and lack of benching limit access to areas above the working floor. Additionally, as mining progresses, it is necessary to monitor different sections of the pit walls. Continually relocating devices is not only costly and time consuming, but can also be dangerous -- especially on unstable slopes.

In an effort to make up for the shortcomings of point monitoring systems, NIOSH is testing several new technologies that will monitor the *entire* slope for rock mass displacement and rock mass composition (Girard and McHugh, 2001; McHugh et al., 2000; Sabine, Mayerle, and others, 1999; Sabine, Denes, and others, 1999; Girard et al., 1998). These technologies include imaging spectroscopy, interferometric synthetic aperture radar, and digital image change detection. Additionally, software has been created under a NIOSH contract to assist geotechnical engineers with bench designs to minimize rock fall hazards (Miller, 2000; Miller, et al., 2000.)

CONCLUSIONS

Slope failures and ground instability at surface mining operations contribute to nearly 15% of surface mining fatalities. Knowing how to properly design slopes with respect to geologic structures will help minimize slope failures. Carefully designed monitoring programs are very useful for supplementing safe operational practices. A properly designed monitoring program will also send warnings of impending instability and provide the necessary geotechnical information for designing appropriate corrective measures. Future technologies may overcome the limitations of current monitoring equipment, but until that time, diligent inspections of the highwalls above workers is crucial. Understanding and recognizing warning signs of impending ground instabilities will hopefully reduce the injury and fatality rates at surface mining operations.

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

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