ASCY

Paper to be presented at Arizona Section AIME, December 3, 1990, Doubletree Inn, Tucson, Arizona.

SLOPE MANAGEMENT STRATEGIES FOR SUCCESSFUL MINING

by

James P. Savely
Cyprus Metals Company
Green Valley, AZ

ABSTRACT

Slope management is anticipation and control of slope behavior. The objective of slope management is to mine in a safe manner and achieve the mine plan. Mining practices need to be modified in unstable areas and mine plans, schedules, and costs should reflect the effects of necessary strategies. An understanding of the causes of instability and the expected slope behavior is essential to successful mining. Failure geometry, strength properties, and monitoring data are important guides in predicting slope behavior. These guides are discussed in more detail regarding the indicators of stability or instability, and whether mining can proceed safely. In addition, methods of establishing movement rate cutoffs and specific responses that need to be in place should movement rates exceed cutoffs are suggested. Effective slope management requires geologic knowledge and contingency planning. This paper describes some of the technical basis and strategies that have been successful in mining with pit slope movement.

INTRODUCTION

Slope management is anticipation and control of slope behavior. It requires a balance of theoretical knowledge and field experience. The objective of slope management is to mine in a safe manner and achieve the mine plan. When losses are incurred from slope movement the problem is often due to the lack of geotechnical evaluation of the mine plan. With proper investigation many slope problems can be anticipated and included as part of the planning process to develop a realistic mine plan. The mine planner has the knowledge of economics and balancing tons and grade with stripping, but he rarely has the geotechnical expertise to determine achievable slope angles.

Geology must be mapped and interpreted ahead of planning and mining. Dewatering devices must be in place in time to provide increased stability and not mined out at a crucial time. Blasting must be controlled on final walls and in sensitive areas to prevent excessive backbreak into the pit walls which can create or aggravate slope instability. Monitoring the slope performance is required for guiding the mining in unstable areas, determining failure geometries, checking design assumptions, predicting slope behavior, ensuring safety, and providing information for redesign when necessary. Periodic field inspection of the slopes in active mining areas is mandated by law and is a part of the monitoring procedure.

Slopes can be designed on stability considerations alone, but stable pit walls do not necessarily mean that the slope has been successfully engineered. A slope that shows no failure may be a too conservative design with maximum profit not realized. Similarly, a slope that appears unstable does not necessarily mean that the slope design is too steep and that safety is being compromised for profit. Economic optimum slopes often have significant instability and there are several examples where mining has been successful and safe while the slope was showing movement (Kennedy and Niermeyer, 1970; Brawner, Stacey, and Stark, 1975; Blackwell and Calder, 1982; Savely and Kastner, 1982). However, failure must be controlled or contained, and movement must be anticipated to provide safety and to minimize economic impact. Responses to slope movement should be thought out and included as part of the mining plan rather than becoming crises that balloon costs, reduce benefits, and perhaps threaten the mine life.

PREDICTING SLOPE BEHAVIOR

Movement vectors, displacement, and velocity of slope movement are determined from observations of prism targets on the pit slope, wireline extensometers, and occasionally more sophisticated monitoring devices. Velocity is a better measure of slope performance than displacement. Consider stability as the ratio of driving stress to resisting stress. When this ratio is greater than one, driving stress exceeds resisting stress and movement occurs. Technically failure has occurred, but yielding rather than collapse often takes place. At high stress ratios more and faster yielding occurs and velocity will increase. Higher stress ratios indicate higher velocities and the stress ratios are determined by the failure geometry and the changes in the stresses as the slope displaces. Stability is decreased by increasing the driving stress, decreasing the resisting stress, or changing both driving and resisting stress. Therefore, predictions of displacement and velocity are related to the failure geometry and the stresses applied due to mining and water.

Displacement and lost access may be only a mining problem and may not be a failure in terms of the mine plan or safety. But, if toes move faster than the mining can advance along a level, the planned ore can be covered by the slide material, and the mine plan will not be achieved. Economic failure has occurred. The objective is to prevent the slope from reaching a velocity that is unrecoverable and prevents mining, and to give sufficient warning so that men and equipment can be moved from an area near a slope that is approaching an unacceptable velocity.

Definition of Failure Stages

Broadbent and Zavodni (1982), defined regressive and progressive failure stages and related these stages to failure geometry. Call (1990) extended their original concept into a useful description of failure characteristics and expected behavior (Figure 1). A slope in the **progressive stage** tends to become less stable with time. The slope will accelerate and displace to total collapse unless active control measures are taken such as slope support, unloading, or slope flattening. Movement can be sudden. The characteristics of these failures are: 1) the failure surface has a dip direction out of the slope and a dip that is flatter than the slope angle but steeper than the sliding friction angle, 2) the total driving force does not decrease with displacement, and 3) the shear strength drops with displacement (peak shear strength greater than residual strength). These type of failures are typical of daylighted structures such as plane shear and wedges formed from faults and other major structure.

A slope that continues to creep at constant velocity with a gradual increase in displacement with time is considered to be in a **steady state**. A steady state slope behavior can change into the progressive stage after considerable movement has taken place due to a reduction in shear strength with time. Steady state behavior usually occurs when: 1) well defined failure surfaces have a dip approximately equal to the sliding friction angle, and 2) shear strength shows no peak strength. Steady state behavior is also noticed with slope instabilities that have undergone large displacements over time where failure surfaces have become well defined and the surface worn down to a nearly complete residual strength.

Characteristics of **regressive stage** failures are: 1) the ratio of driving stress to resisting stress decreases with displacement, and 2) the slope will tend to become more stable with time and show decelerating or stick-slip behavior. The cumulative displacement graph appears cyclical and the cycles will generally correspond with changes in external forces such as mining activity, blasting, and rainfall. The slope will tend to restabilize if the external forces are removed. The movement rate typically fluctuates with time. These types of movement are associated with rock mass failure, deep-seated rotational failure, time dependent strength properties, or complex failure geometries such as active-passive blocks. Failures that show toe heave, such as non-daylighted failures with horizontal or upward movement at the toe, are typically regressive. An important consideration is that **regressive failures can become progressive** when: 1) mining daylights a previously non-daylighted failure or new failure surface, 2) the rock mass at the toe breaks up and a shear surface or shear zone is developed, 3) water pressures increase, or 4) when mining is continued or increased without letting the slope regain equilibrium, and the slope accelerates beyond recovery. Figure 2 shows examples of displacement graphs for the three stages. Figure 3 shows typical velocity graphs. Because of fluctuations in the velocity calculations, it is important to look at at a long time history and the upper and lower bounds to determine trends.

Predicting Equations

Velocity projections are useful for looking at mathematically fitted trends and estimating future displacement rates. The procedure recommended by Zavodni and Broadbent (1978) is to plot the log of velocity (incremental velocity or incremental cumulative velocity) versus time. The displacement record appears to be exponential so generally the data plot on a straight line with a change in slope at the onset of progressive stage failure. For example, in Figure 4 the onset of progressive stage failure for the data is interpreted to be at 21 days with a velocity, V_o, of 5.5 cm/day (.18 feet/day).

Assuming t=0 at the onset of progressive stage failure, the equation for the progressive stage line is:

$$V=V_o e^{Bt}$$

where:

V is velocity
V_o is the velocity at t=0 (onset of progressive stage)
B is slope of the velocity-time line
t is time in days
e is the base of natural logarithm

The plot of the data is examined for a change in slope that is expected to occur at the onset of progressive stage failure. A regression fit is made to the first trend of data points. A second regression fit is made on the second trend of data points. The point where the two regression lines intersect is where t=0, which determines V_o. Zavodni and Broadbent (1978), developed an empirical relationship to predict the collapse velocity, V_{col}. They plotted data on numerous failed slopes from different mines as log of velocity versus days prior to collapse and estimated that the collapse velocity could be predicted by the equation:

$$V_{col}=K^2 V_o$$

where K is an empirical constant that represent the slope of the progressive failure regression line. For known failures with historical data, K can be determined exactly for a slope by determining V_o and V_{mp}. V_{mp} is the velocity at the mid-point between the onset of progressive stage failure, Vo, and the velocity at the time of collapse, V_{col}, and

$K=V_{mp}/V_o$

A single value of velocity, V_o, for the onset of progressive failure cannot be generalized to all failures. V_o, must be determined for each specific failure based on monitoring history. Experience using the exponential predicting equation indicates that there may be a continuous acceleration rather than an abrupt collapse point. Also, as the acceleration increases, extrapolation from linear regression becomes less precise. This means that there are probably more than two stages prior to collapse as suggested by Cruden and Masoumzadeh. Call (1990) suggests that additional regressions should be done with a new evaluation done after each new data point is plotted.

Velocity Cutoffs and Relaxation Levels

The decision to "live with" slope failure and continue to mine should be made only for regressive or steady state failures. It will be necessary to determine velocities acceptable for safe mining without forcing the failure into a progressive stage. If velocity exceeds the criteria, mining will be discontinued until an acceptable relaxation velocity is achieved. The criteria that is developed determines the economics of the mining.

Stability of many slopes can be controlled if only small displacement is allowed before mining is stopped and the slope is allowed to relax. If mining continues until the slope is at a high velocity it will usually take a longer time for the slope to return to equilibrium. If the slope is pushed too far or if hydrologic conditions change, it may accelerate to the progressive stage and collapse. More frequent pullouts with short mining periods and short time delays may be preferable to long mining periods with fewer pullouts and extended time delays. The geometry and strength characteristics of the failure are indicators of expected displacement, velocity, and time to recovery.

For mining plans with multiple pushbacks, monitoring data combined with mining history is the best information to determine achievable mining rates, velocity cutoffs, and relaxation levels. This requires frequent readings on the movement in the early stages of mining to determine velocities experienced and the time required for velocity to recede to a steady state. The criteria is developed with close monitoring and by letting velocities increase in small steps to higher levels and observing the time required for the slope to recover to a steady state. In the regressive stage, higher velocities will usually require longer relaxation periods. This process should be done under the guidance of slope engineers to keep the slope under control. Experience has shown that the criteria is site specific and acceptable velocities can be as high as a few meters per day and as low as a few centimeters per day depending on the failure characteristics. Relaxation velocities can also have a similar wide range.

GEOLOGY

Changes in geologic relationships with the pit wall orientation need to be anticipated for each pushback before the plan is implemented. This requires routine geologic mapping and interpretation to keep the geology current and to determine if assumptions made in the slope stability analysis are valid. Interpreted geology level maps and current geology on pit composites and mining sequence maps are essential tools for evaluating and managing pit slope instability. These maps tell you where you are and where you are going in terms of the slope design.

I have found that by keeping a current composite geology map it is possible to explain stability concerns to operations personnel. In one instance we were able to modify a blasting pattern to reduce backbreak along a major fault. In another instance it was possible to prevent failure of a haul road near the bottom of the pit because the geology projected from the mapping indicated that a failure geometry would be undercut and fail half of the road. Mining concentrated in other areas of the bench and the haul road was intentionally undercut after most of the material had been mined. In another situation it was possible to locate a pump well where it would be more effective for dewatering because the groundwater was compartmentalized between faults that had been mapped and located on the pit map.

CONTINGENCY PLANNING

If slope movement is expected, then contingency planning is necessary to minimize the impact of slope failure and to provide a realistic plan. Contingencies that have proven successful are to:

1) **Provide dual or multiple access to the ore faces and pushbacks.** Although this may increase stripping requirements, if access to the ore is lost or production is disrupted the consequences can be costly. With only one access the slope design must be more conservative to ensure production and this also results in increased stripping and risk to the mine plan. For slopes that have a history of movement even a conservative slope angle may not guarantee continued production, thus making multiple access a better choice.

2) **Stockpile sufficient ore to maintain production during periods of no mining.** The tonnage requirements depend on whether other contingencies are available and the anticipated length of time required for the slope to return to an acceptable velocity for mining.

3) **Establish additional ore faces before instability occurs.** The number of additional ore faces required depends on the extent of stability problems and the orebody characteristics. The objective is to create as many alternative ore sources as possible to provide flexibility.

4) **Plan wide pushbacks.** In large mines wide pushbacks provide the flexibility to simply mine around the failure area and come back later to mine final limits when the movement rate has decreased. The stripping requirements are increased, but this is usually a better option than the delays, constrained mining, and deferred ore that result from failures that affect more confined working areas.

5) **Plan a stepout.** Depending on the orebody configuration it is often possible to plan a stepout for slopes that are expected to show slope movement. The exact level where the stepout is needed may not be known and difficult to determine, but a best guess or an arbitrary level can be taken to account for the most likely event. During mining, if movement requires the stepout then the plan can still be met. If the stepout becomes unnecessary then additional ore might be gained. This is a strategy that provides realistic mine plans in historically unstable areas.

6) **Use dynamic sequencing to add lag times.** Most sequencing is done to balance ore tons and grade with stripping to even out capital flow and keep it under control. Most planners do not formally include geotechnical aspects in the sequencing (Couzens, 1990). Dynamic sequencing can be done in areas of expected instability where planned periods of slow or no mining are included to provide flexibility and a realistic mining rate. It is similar to lag time in project scheduling where early start/finish and late start/finish can be defined. For some large scale failures it is possible to adjust the sequencing to minimize slope heights and to minimize forces that contribute to instability.

7) **Provide for failure costs in scheduling and budgeting.** This might include estimates of extra tonnage for slide cleanup, additional haulage costs, deferred ore and stripping, production delays , haulroad repairs, and stepouts.

8) **Design to prevent noses in the plan geometry.** It is well known that noses are generally less stable than straight or concave pit walls. Most planners try to minimize noses in their plans, but in mine operations noses can develop because of unachievable geometry. This can happen where different phases of mining join together along a pit wall (Figure 5). An unplanned nose that is left is just as unstable as a planned nose and a needless slope failure can result. Frequently operations cannot mine to

the precise corners required by the plan. The planning engineer can anticipate these operations problems and provide for them in the design (Clark, 1990).

OPERATIONAL CONSIDERATIONS

There are a few specific activities in mine operations that need to be done to improve slope stability and to provide for better mining. Operational considerations include:

1) **Locating sumps in areas where seepage will not affect stability.** Usually sumps located in the bottom of a pit away from the toe of the slope are acceptable. In deep mines the water will have to be staged to higher sumps. These sumps should be lined or otherwise sealed to prevent seepage into the pit wall. The number of sumps should be kept to a minimum. Sump placement and dewatering schemes should be planned through the life of the mine using the mine sequence maps.

2) **Eliminating or controlling flows of water that enter into slopes and operating areas from natural sources, leach dumps, tailings dams, processing facilities, and pipelines.** Storm runoff should be diverted around unstable areas and the pit perimeter in general. To prevent water from entering tension cracks, the crest and upper slopes of failures should be covered and contoured to provide for fast runoff. Small steady flows into tension cracks or on the slope have a worse effect than occasional large flows from storm runoff. In a typical fractured rock mass, assuming 5 percent of the volume can be considered open space between fractures, a volume of dry slope 150m (500 feet) high, 150m (500 feet) long, and 60m (200 feet) deep (approximately 4 million tons) could hold 72 million liters (19 million gallons) of water. Without drainage and a recharge of 75 l/min (20 gpm) all of the available open space will be filled with water in less than 2 years. Therefore, if there is 75 l/min (20 gpm) more going into the slope than is being drained from the slope, the slope will be completely saturated in less than 2 years and stability will be reduced. It is more likely that failure will occur before the slope is completely saturated.

3) **Reviewing and implementing controlled blast designs in sensitive areas.** Blast damage is generally considered to be excessive backbreak on benches and along major structure. A general statement is that charge per delay, powder factor or energy, and subgrade drilling should all be decreased as the final pit wall or the sensitive slope is approached (Savely, 1989).

4) **Comparing pit geology with mine advance to anticipate slope problems and guide the mining.** This is applied geology and it requires that mapping be current and the geology interpreted in time to be useful. The information can be communicated to operations in weekly production meetings.

RESPONSES TO SLOPE MOVEMENT

Stewart and Kennedy (1971), discuss actions that can be taken in response to slope instability. Call (1990) has developed these ideas further and suggests eight responses to slope movement:

1) **Leave the unstable area alone.** This option can be taken when instability is in an abandoned or inactive area.

2) **Continue mining without changing the mine plan.** If the velocity is low and predictable, and the area must be mined, living with the displacement while continuing to mine may be the best alternative. This course of action requires a good monitoring system, an understanding of the failure mechanics, and historical information on the slope behavior.

3) **Unload the slide through additional stripping.** Even though unloading has been a common response, in general it has been unsuccessful. In fact, there are situations involving high water pressure where

unloading actually decreases stability. The failure geometry and the failure mechanics must be understood to ensure that unloading will stabilize the failure.

4) **Leave a stepout.** Stepouts have been used successfully in several mines. The choice between stepout and cleanup is determined by the trade-off between the value of lost ore and the cost of cleanup.

5) **Do a partial cleanup.** Partial cleanup may be the best choice where a slide blocks a haulroad or fails onto a working area. Only that material necessary to get back into operation needs to be cleaned up.

6) **Mine out the failure.** Where the failure is on a specific structure and there is competent rock behind the structure, mining out the failure may be the optimum choice. Structure and failure geometries are often repeating so good geologic interpretation is essential to determine if the new slope will be stable.

7) **Support the unstable ground with cable bolts.** Mechanical support may be the most cost-effective option when a crusher, conveyor, or haulroad must be protected.

8) **Dewater the unstable area.** Where high water pressure exists, dewatering is an effective method of stabilization that may be used in conjunction with other options. There are few cases where it is cost effective to live with the effects of high water pressures. An extensive dewatering program that will stabilize slopes can be implemented and maintained for about the same yearly cost as 15 to 20 shifts of stripping. The potential savings in stripping by achieving steeper slopes and reducing failure removal costs because of dewatering can be 1000 shifts or more over the life of the mine. A good discussion of practical dewatering is given in Rantapaa (1990).

CONCLUSIONS

Good monitoring information and knowledge of the failure characteristics allow the slope engineer to define the stage of a slope failure as being progressive, steady state, or regressive. For steady state and regressive type movement it is possible to implement a slope management program to "live with" the movement and to continue mining safely. If slope movement is expected it is necessary to develop contingency plans to minimize the impact of slope movement and to provide a realistic plan. Responses to slope movement should be part of mine planning and alternative responses evaluated with a cost-benefit study. When slope movement occurs the appropriately planned alternative can be implemented instead of a costly, unplanned crisis response that may not deal effectively with the slope problem. Mine operations are also responsible in successful slope management. They should control water and revise blasting practices in sensitive areas.

REFERENCES

Blackwell, G.H. and Calder, P.N. 1982, "Practical Aspects of Wall Stability at Brenda Mines Ltd., Peachland, B.C.", Proc. Third Int'l. Conf. on Stability in Surface Mining, Ch. 25, C.O. Brawner, ed., AIME, New York, pp. 573-608.

Brawner, C.O., Stacey, P.F., and Stark, R., 1975, "A Successful Application of Mining with Pitwall Movement", paper presented to Western Annual Meeting, Canadian Institute of Mining, Edmonton, Alberta, October 26-29, 1975.

Broadbent, C.D. and Zavodni, Z.M., 1982, "Influence of Rock Structure on Stability", Proc. Third Int'l. Conf. on Stability in Surface Mining, Ch. 2, C.O. Brawner, ed., AIME, New York, pp. 7-18.

Call, R.D., 1990, Personal Communication.

Call, R.D., 1982, "Monitoring Pit Slope Behavior", Proc. Third Int'l. Conf. on Stability in Surface Mining, Ch. 9, C.O. Brawner, ed., AIME, New York, pp. 229-248.

Cruden, D.M. and Masoumzadeh, S., 1987, "Accelerating Creep of the Slopes of a Coal Mine", Rock Mechanics and Rock Engineering, v. 20, pp. 123-135.

Clark, J.W., 1990, Personal Communication.

Couzens, T., 1990, Personal Communication.

Kennedy, B.A. and Niermeyer, K.E., 1970, "Slope Monitoring Systems Used in the Prediction of a Major Slope Failure at the Chuquicamata Mine, Chile", Planning Open Pit Mines, Proc. Symp. on Planning Open Pit Mines with Special Reference to Slope Stability, A.A. Balkema, Amsterdam, pp. 215-225.

Rantapaa, M. D., 1990, "Mine Dewatering Procedures at Cyprus Miami Mining Corporation", paper presented at Goldtech 4, Sept. 10-12, 1990, Reno, NV (also available in 1990 AIME preprint) 12 pp.

Savely, J.P., 1989, "Designing a Final Wall Blast to Improve Stability", Trans. AIME, v. 284, pp. 1869-1877 (also available in 1986 AIME preprint).

Savely, J.P. and Kastner, V.L., 1982, "Slope Instability at Inspiration's Mines", Proc. Third Int'l. Conf. on Stability in Surface Mining, Ch. 26, C.O. Brawner, ed., AIME, New York, pp. 609-634.

Stewart, R.M. and Kennedy, B.A., 1971, "The Role of Slope Stability in the Economics, Design and Operation of Open Pit Mines", Proc. First Int'l Conf. on Stability in Open Pit Mining, Ch. 2, C.O. Brawner, ed., AIME, New York, pp. 5-21.

Zavodni, Z.M. and Broadbent, C.D., 1978, "Slope Failure Kinematics", Proc. 19th U.S. Symposium on Rock Mechanics, May 1-3, pp. 86-94.