Assessing slope performance

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Abstract

Chapter 12 of the Guidelines for Open Pit Slope Design (CSIRO (1)) provides a comprehensive review of the principles and methodologies for assessing slope performance, reviews slope monitoring techniques, provides guidelines for establishing slope monitoring programs, and introduces the concept of ground control management plans. This paper presents a summary of the key concepts and techniques for assessing slope performance at the bench, inter-ramp and overall slope scales.

INTRODUCTION

In most open pit mines, the physical environment in which slope designs must be developed and implemented is extremely complex. Despite the growing sophistication of computer modeling techniques, we do not (and likely never will) have the data or analytical ability to explicitly model this natural complexity. Consequently, we must use simplified models to depict the distribution and characteristics of the soil, rock and groundwater. These models are invariably based on incomplete information and subjective interpretations, and our confidence in them is often affected by tight investigation budgets and schedules, and practical limitations of the available tools and techniques. This problem is particularly acute on projects where there is little or no previous mining history, exposures are scarce, drillholes are widely spaced, and/or instrumentation is lacking.

Given this reality, ongoing empirical "calibration" of the key factors that influence open pit slope design, and validation of the design methodology and criteria, are necessary components of a rational slope design program. In this context, slope design must be considered as an iterative process whereby:

- Design criteria are developed based on the best information available and a transparent and defendable methodology;
- Slope designs are implemented according to the established criteria;
- Actual geologic conditions, as-built slope geometry and slope behaviour are documented;
- Documented conditions and behaviour are compared to initial predictions, expectations, and assumptions; and
- Assumptions, methodologies and design criteria are modified accordingly, completing the cycle.

This process requires systematic monitoring and documentation of geologic conditions and slope performance, and periodic updates of the design criteria and mine plans as the mine develops.

VALIDATION OF THE GEOTECHNICAL MODEL

The validity of the geotechnical model (and constituent geology and groundwater models) must be periodically checked to ensure that it is as accurate as possible and reflects the most current information and interpretations. Periodic revision and updating of the model as the mine is developed and more information becomes available will help to improve confidence in the design.

Geological Mapping

Ongoing geological mapping as the rock mass is exposed by mining is essential to correlate major structures and verify structural domain boundaries and lithologic, alteration and mineralization contacts, and reconcile the geological block model. Very useful information on lithology, alteration and mineralization can also be obtained from infill drilling programs and systematic logging of blasthole cuttings.

Bench Mapping

Benches provide excellent opportunities for correlation of major structures, detailed structural fabric mapping and characterization of discontinuities. Initial bench exposures often provide the first opportunity for measurement of important characteristics such as discontinuity spacing, continuity and waviness, which are not possible to reliably measure in drill core. Information obtained from bench mapping programs can be used to update and refine structural domain boundaries, and to confirm the shear strength characteristics of the discontinuities. Suitable bench mapping techniques include traditional line and widow mapping, as well as the use of modern laser scanning and photogrammetric mapping techniques.

Supplementary Investigations

As the mine develops and the understanding of the geological framework of the deposit evolves, questions regarding the validity and accuracy of the underlying interpretation often emerge. Specific geotechnical and hydrogeological issues may require further investigation and analysis. In these cases, targeted supplementary drilling may be needed to confirm the geology and rock mass characteristics, obtain samples for index and laboratory testing, locate and orient key structures or fabric, evaluate hydrogeologic characteristics, and install instrumentation.

BENCH PERFORMANCE

Systematic documentation and evaluation of the performance of benches should be a key component of any slope performance assessment program. Benches are the fundamental building blocks of the slope, and their geometry and behaviour often controls the inter-ramp and overall slope design. Bench performance assessments should compliment bench mapping exercises and capture data on the as-built geometry of the benches, the geomechanical characteristics of the rock mass, the impact of blasting and excavation, the degree and type of structural control, bench-scale failures, and the general behaviour of the bench.

Bench Documentation

Figure 1 is an example of a typical format for collecting key bench performance data using a documentation window approach.

BENCH DOCUMENTATION FORM

PHASE:	STRUCT. DOMAIN:	STATION:
WALL:	ROCK TYPE:	DATE:
SECTOR:	ALT. TYPE:	DOCUMENTED BY:
BENCH:	ALT. INTENSITY:	PHOTOS:

ROCK MASS CLASSIFICATION

Parameter	Value of Parameter Min.	Max.	Ave.	Rating
Degree of Alteration				
Degree of Breakage				
Hardness (ISRM)				
Intact Strength (MPa)				
RQD (%)				
Joint Spacing (m)				
Jv (#/m3)				
Joint Condition				
Groundwater Conditions				
ROCK MASS RATING (RMR 76)				
GSI - Surface Conditions				
GSI - Structure				
GEOLOGICAL STRENGTH INDEX (GSI)				

BENCH GEOMETRY

Bench Height (m)				
Bench Face Angle(°)				
Bench Face Azimuth(°)				
Effective Berm Width (m)				
Unfilled Berm Width (m)				
Shape of Bench Face:	Planar	Convex	Concave	Irregular

DEGREE OF STRUCTURAL CONTROL

N	W	M	S	VS

CONTROLLING FAILURE MECHANISM(S)

BLASTING

Type:
Pattern:
Identification No.:

BLAST DAMAGE TO BERM

N	W	M	S	VS

Distance of Cracking Behind Crest (m):
Comments:

BLAST DAMAGE TO FACE

N	W	M	S	VS

Comments:

OTHER COMMENTS OR OBSERVATIONS

DISCONTINUITY SETS

Set No./ Name	Type	Dip. Dir. (°)	Dip (°)	Length (m)	Spacing (m)	JC	JRC	JCS	Jr	Ja	Jw	
1 /												
2 /												
3 /												
4 /												
5 /												
6 /												

PHOTO /SKETCH

LOWER HEMISPHERE PROJECTION

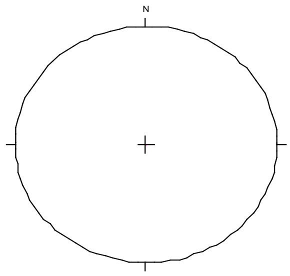

Figure 1 - *Typical Bench Documentation Form*

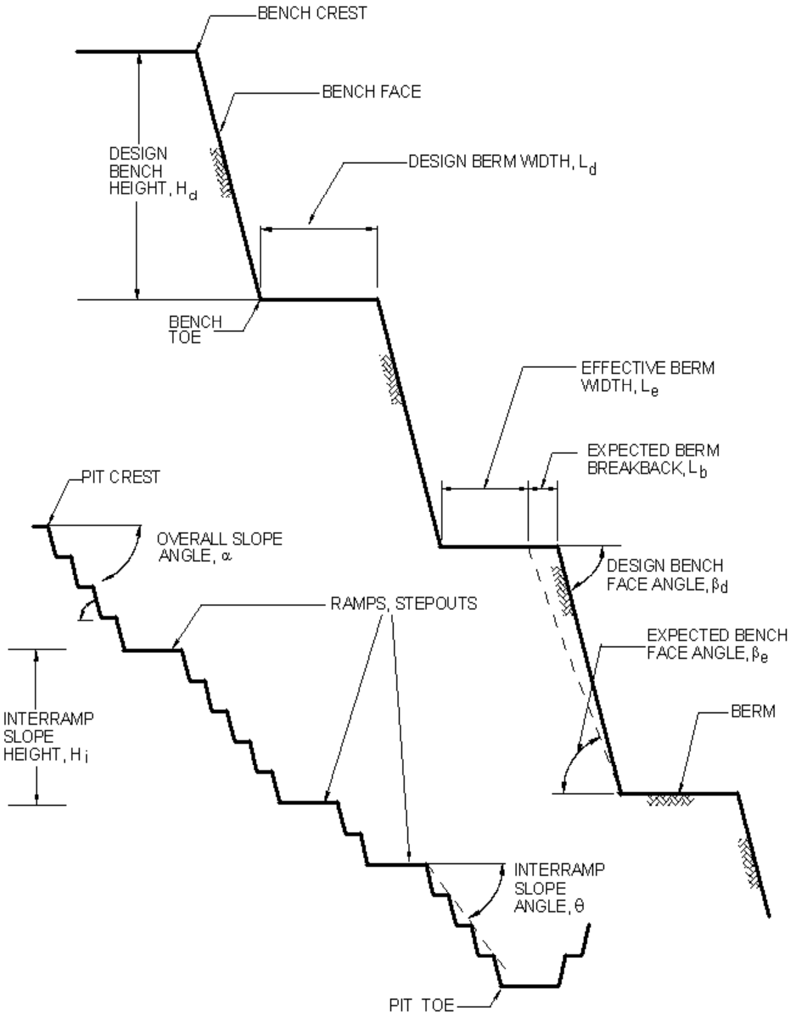

Figure 2 - *Basic Slope Geometry Parameters*

Rock Mass Classification

Bench documentation and mapping should facilitate collection of all of the parameters required to classify the rock mass using an industry standard rock mass classification system such as GSI (Hoek et al (2)), RMR (Bieniawski (3)), Q (Barton et al (4)), MRMR (Laubscher (5)), or a system customized to the specific site (e.g., Hawley et al (6)). The system should be compatible with the underlying rock mass model so that the classification data can be used to validate and refine the model and design assumptions concerning rock mass competency and strength. Comparison of predicted vs. documented rock mass competency in a given geotechnical unit or rock mass domain will provide an indication of the reliability of the model, and incorporating this data into the model should help to improve confidence.

Bench Face Angle

Most bench and inter-ramp slope design methodologies rely heavily on predictions of expected bench breakback in response to mining. One of the key parameters used to define bench geometry is the expected (or effective) bench face angle (β_e) (Figure 2). β_e is the angle to which the bench face is expected to breakback during mining, and is a complex function of many factors, including: the structural fabric, the condition of the discontinuities, the competency of the rock mass, the blasting and excavation technique, scaling and toe cleanup, environmental factors, and exposure period. Because it is impossible to explicitly account for all of these factors, systematic documentation of as-built bench face angles and comparison of this data to expected breakback predictions is essential to validate and calibrate the design methodology used to predict β_e.

There are several approaches available for documenting as-built bench face angles, but digital photogrammetry or laser scanning techniques are probably the most accurate. Both of these methods facilitate development of high quality digital topographic models that can be used to develop statistically reliable distributions of as-built bench face angles. Histogram plots and cumulative frequency analysis are convenient ways of presenting and evaluating as-built bench face angle (β_a) data and comparing the results to original β_e predictions. Figure 3 shows comparison of the distributions of β_a and β_e for a hypothetical design sector. In this example the two distributions are coincident at a cumulative frequency of 40% and a bench face angle of 65°. For cumulative frequencies of greater than 40%, as-built bench face angles are flatter than expected breakback angles. One explanation for this discrepancy might be that excessive blast damage at the bench crest has exacerbated breakback. For cumulative frequencies of less than 40%, as-built breakback angles are steeper than expected breakback angles. This discrepancy could indicate that the predictive kinematic analysis assumed conservative continuity and spacing values for key discontinuity sets that control breakback. Other factors could also lead to these discrepancies; hence the importance of documenting and evaluating factors other than just the bench geometry, such as the degree of structural control, observed failure mechanisms, the shape of the bench face, and the impact of blasting.

Cumulative frequency (CF) analysis also provides a convenient tool for objectively evaluating bench performance based on established acceptability criteria. For example, if unacceptable performance is defined as an as-built bench face angle that is flatter than the expected breakback angle, acceptability criteria could be based on a specific CF threshold, taking into account confidence in the model and analysis technique, consequences of failure and overall risk tolerance. This is analogous to a probability of failure (PoF) analysis. In a critical design case where confidence is low, consequences are high and/or risk tolerance is low, a CF (or PoF) of 20% might be appropriate. In practical terms this means that it would only be acceptable for less than 20% of the bench to breakback to an angle that is flatter than the nominal design bench face angle (β_d). Alternatively, where confidence is high, consequences are low and/or risk tolerance is high, a CF (or PoF) of 50% might be acceptable. In either case, if sufficient as-built bench face angle data is available, bench performance can be objectively evaluated using CF analysis. Figure 4 illustrates this concept using hypothetical as-built bench face angle distribution curves from two different design sectors: Curves A and B. In both cases, evaluation of acceptable performance is based on a β_e of 65° and a target CF of 35%. Curve A indicates a β_a of 60° at a CF of 35%. In this case the slope is not performing adequately and a revision to the design criteria and/or modification of excavation procedures is required. Curve B indicates a β_a of 70° at a CF of 35%. In this case the slope is performing adequately, and consideration might be given to steepening the design or relaxing excavation controls.

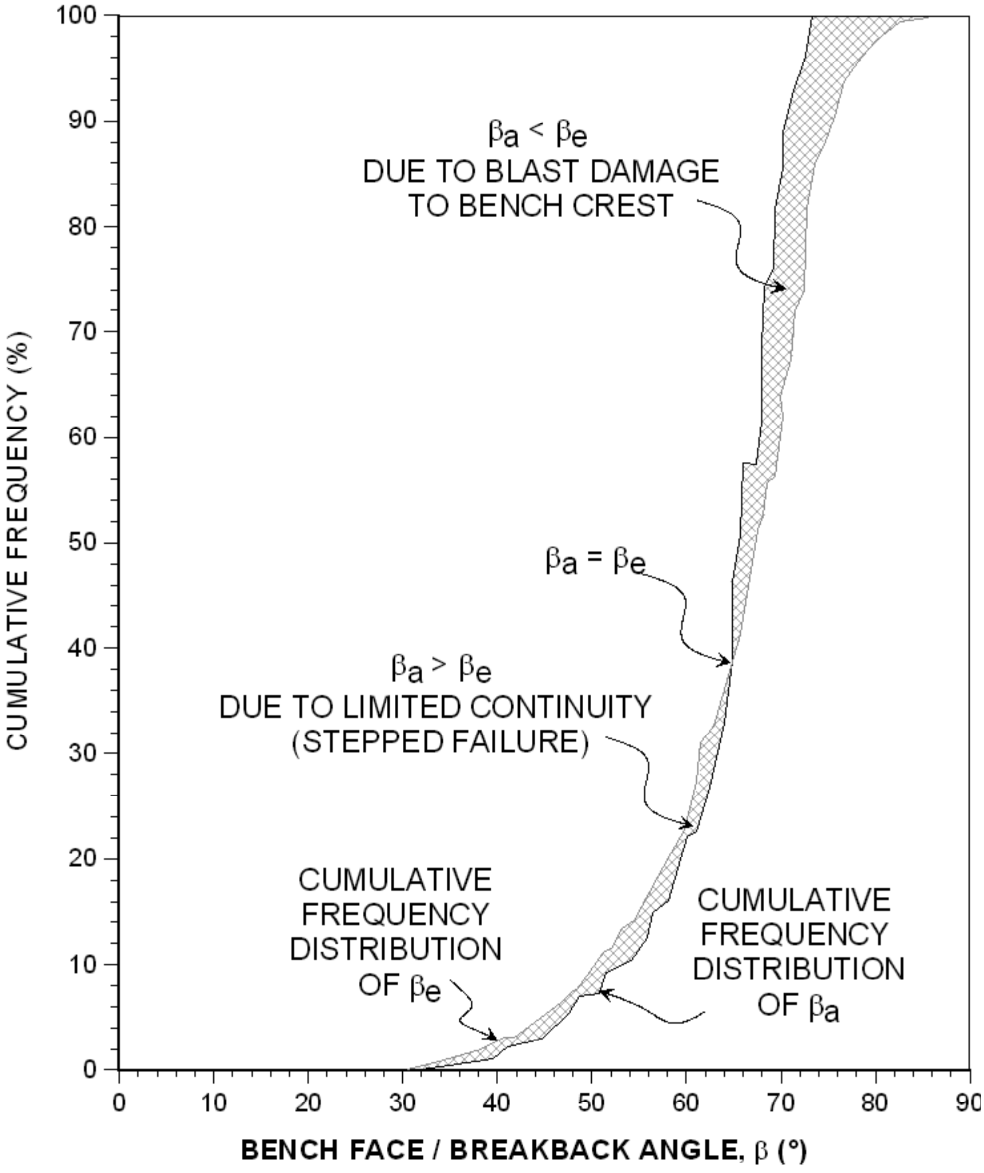

Figure 3 *- As-built Bench Face Angle vs. Expected Breakback Angle*

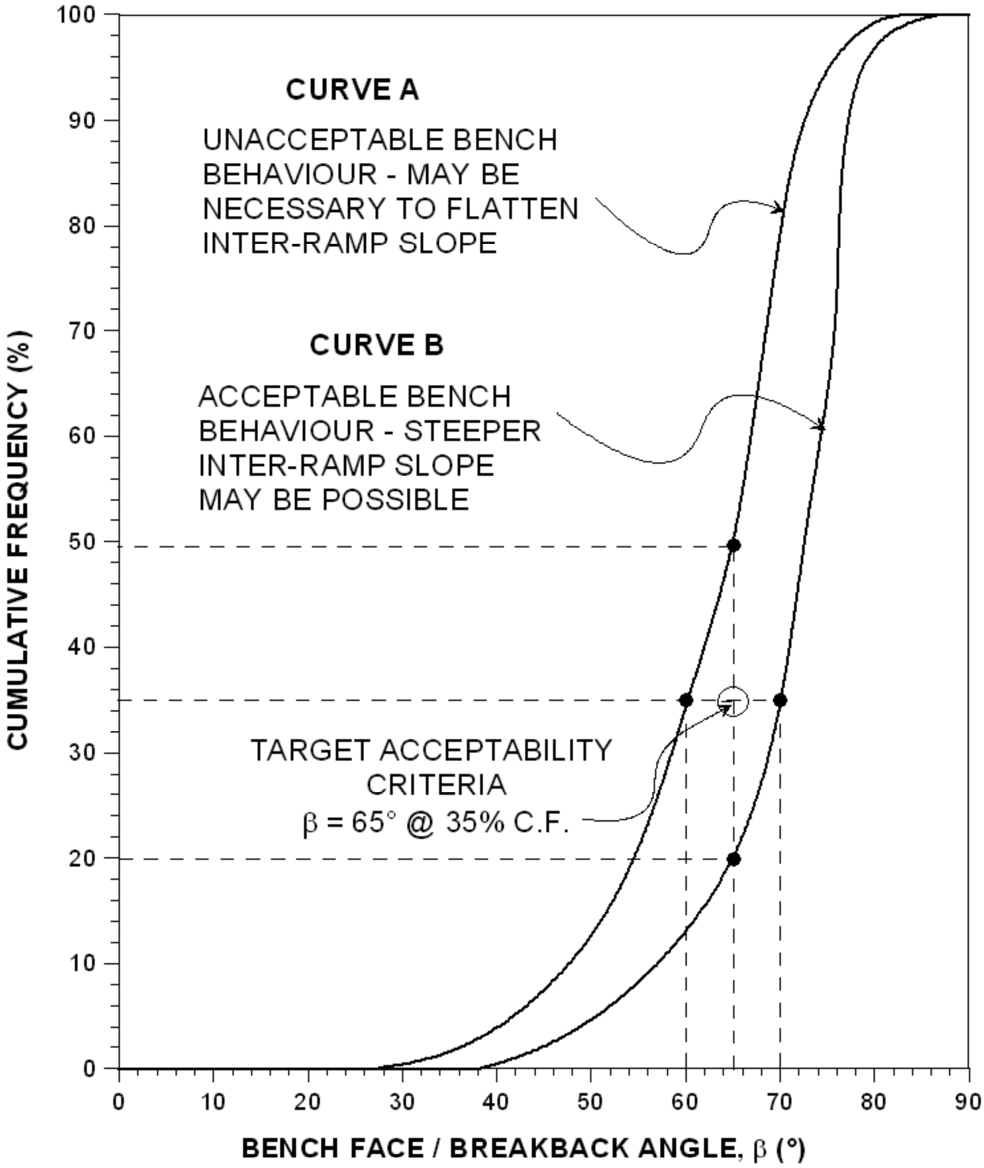

Figure 4 *- Assessment of Bench Performance Using Cumulative Frequency Analysis*

Berm Width

As illustrated in Figure 2, the design inter-ramp angle (θ_d) is defined by the design bench height (H_d) and either the design bench face angle (β_d) and design berm width (L_d), or the expected breakback angle (β_e) and expected (or effective) berm width (L_e). Bench height is usually fixed based on equipment specifications. In the context of this discussion, L_e is defined as the width of the catchment berm that remains following excavation, scaling and cleanup of the bench, and may be based on variety of objectives and criteria, including: the competency of the rock mass, the height of the bench, the volume of potential bench-scale failures, rockfall catchment criteria, access requirements, service life of the slope, inter-ramp slope angle and height, general risk tolerance, and other factors. Comparison of as-built versus expected berm width provides another opportunity for objectively assessing bench performance. As for bench face angles, laser scanning or photogrammetric methods likely provide the most convenient and accurate methods for documenting as-built berm widths, and similar CF analysis techniques as described above can be used to analyze the data and assess conformity to design.

Effectiveness of Catchment

While comparison of as-built vs. expected bench face angles and berm widths can be used to evaluate whether or not the design intent is being met, bench performance assessments should also evaluate the effectiveness of the design. The primary purpose of benches is to provide catchment for bench-scale failures, raveling debris and rockfalls, and thus provide a safe working environment for equipment and personnel. Benches also establish platforms for electrical infrastructure, dewatering infrastructure, instrumentation and surface water management, and provide access to the slope for mapping, documentation and visual inspection. Benches should be inspected periodically to assess whether or not they are meeting these needs.

Blasting

The process by which the bench is excavated (i.e., the design and sequencing of blasting and the type of equipment and technique used to excavate the bench) can have a significant (and often controlling) influence on bench performance. Unlike the underlying geological and geotechnical characteristics, which are fixed, the impact of blasting and excavation on wall stability can be controlled. Because blast design remains largely an empirical process (not unlike the slope design process), carefully designed blasting trials that include vibration monitoring and systematic modification of key design parameters are usually required to achieve the optimum balance between minimizing damage to the rock mass and achieving adequate fragmentation and excavation productivity. Key parameters that need to be considered in designing wall control blasts include: the type of blast (e.g., buffer, pre-split or trim); the diameter, inclination, layout (spacing and burden) of the blastholes; the type, amount and distribution of explosives within individual blastholes and the blast pattern; and the size of the blast and sequencing of delays.

Bench Excavation and Design Compliance

Once the blast has been shot, removal of the blasted muck requires careful survey control to ensure that design crests and toes are respected. In poor quality rock masses, the use of large cable shovels or loaders may result in over-digging and loss of catchment berm width. In these cases it may be necessary to profile the final bench using hydraulic excavators, backhoes or bulldozers. In more competent rocks, under-digging as a result of “hard toes” can force the slope off design or result in narrowing of subsequent catchment berms to compensate. In this context, bench performance assessments should also consider tracking compliance with respect to the design lines for bench crests and toes. Variance data can be obtained from crest and toe surveys or using laser scanning or photogrammetric techniques, and analyzed and presented using histograms or CF analysis as described above.

Scaling and Cleanup

Scaling of the bench crest and face following excavation is an important component of the excavation cycle that is sometimes overlooked or ignored. Scaling is intended to remove loose blocks and slabs that could form rockfalls or small failures that could create potential safety hazards. Scaling also minimizes the amount of debris that collects on the bench following excavation, thus preserving valuable catchment volume.

Primary scaling is often conducted on a second pass along the face by the same shovel or excavator that removed the original blasted muck. Depending on the nature of the rock mass, the bench height, the size of the shovel/excavator, operator experience, and the design catchment berm width, this may be sufficient. However, in many circumstances, secondary scaling using specialized equipment and techniques is required to achieve optimum results. Special equipment might include a dedicated long-boom excavator that operates from the working level (Photo 1), or a backhoe or bulldozer with a scaling chain operating from the catchment bench. Scaling is best accomplished before access become difficult or is lost, and before final cleanup at the toe of the bench.

Photo 1 *- Long-boom Scaling Backhoe (courtesy, Compañia Minera Antamina S.A.)*

Bench inspection programs should include specific assessment of the condition of the catchment bench, crest and face following initial scaling efforts to identify sectors where additional work is required. Areas requiring supplemental scaling should be identified on a bench maintenance plan. Cleanup of debris that accumulates at the toe of the bench should be conducted immediately following scaling, before access to the toe is lost. Any debris left on the bench reduces the effectiveness of the catchment. In some circumstance, supplementary cleaning or redistribution of debris that has accumulated on the bench may be necessary to maintain adequate catchment. Supplementary bench cleaning will depend on available access and the service life of the slope. As for supplementary scaling, periodic bench inspections should identify bench sectors that require cleaning, and these should be identified on a bench maintenance plan (e.g., Figure. 5).

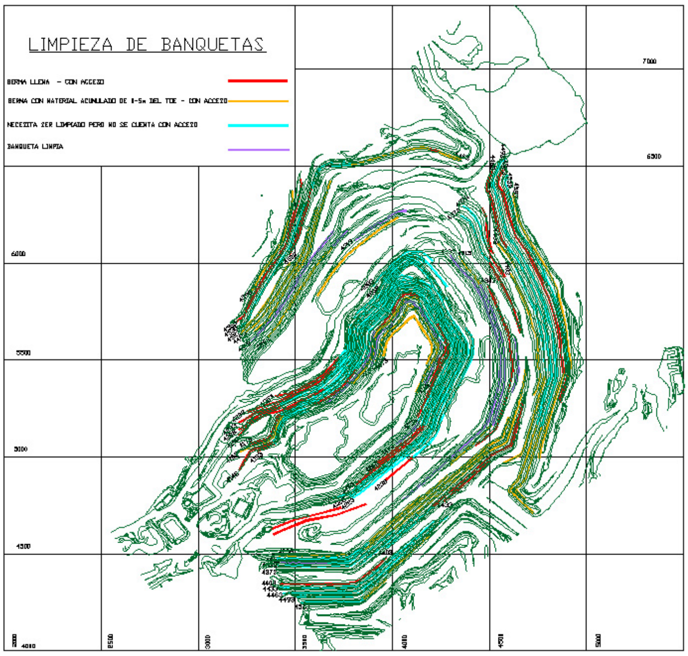

Figure 5 *- Bench Cleaning Plan (courtesy Compañia Minera Antamina S.A.)*

Bench Failures

The occurrence and nature of bench-scale failures can provide important insights into the effectiveness of the bench design criteria and underlying assumptions regarding failure mechanisms, persistence and spacing of key discontinuity sets, and risk tolerance. Sensitivity and back analyses of these failures can help to validate and refine shear strength assumptions. Plans that depict the location, type and extent of bench-scale failures can help focus attention on design sectors that may require closer surveillance or design adjustments to mitigate higher risk levels. A registry of all significant bench failures should be maintained. This registry should contain the following information:

- A unique identifier
- Location (UTM or mine grid coordinates, phase, sector, bench)
- Date bench was completed and date of failure
- Description of the type of failure (wedge, planar, toppling, stepped, rotational, complex)
- Orientation, spacing and persistence of individual discontinuities or sets involved
- Stereographic projections, sketches and/or plans illustrating the failure mechanism
- Planarity, roughness and infilling characteristics of discontinuities
- Structural domain, lithology, alteration, mineralization, rock mass unit
- Triggering events (blasting, seismic, precipitation, freeze-thaw, no apparent cause) Bench height, width of catchment berm, width filled by debris from failure, remaining effective width
- Results of back analyses
- Photographic documentation
- Inspection reports; notes on any precursors (tension cracks, rockfalls, raveling)

Composite Bench Performance Indices

As discussed above, there are a plethora of factors that influence bench performance, and documenting and evaluating each individual factor and evaluating their relative influence can be challenging. To help simplify evaluations of bench performance, some mines focus on one or two key performance indicators (KPIs) that they feel are critical to their operation, such as compliance with the design crest, bench face angle or berm width. Other mines have adopted composite indices that evaluate and weight a wide variety of factors using various semi-empirical criteria. Figure 6 is an example of a system that is currently being implemented on a trial basis at the Rosario mine in Chile, and is based on an approach being used at the Chuquicamatta mine (CSIRO (7)). In this system, two factors are evaluated: one that represents design compliance

– the Design Factor (F_d), and one that represents the condition of the slope – the Condition Factor (F_c). F_d is calculated based on a weighting of four objective (and inter-related) parameters: the berm width, L; the inter-ramp angle, θ (calculated based on the as-built berm width and bench face angle); the face angle, β; and compliance with the design toe (Δ). The distributions of the values for each of these parameters are determined for a specified wall sector (in this case corresponding to a wall control blast pattern) and compared to their respective design values and a specified tolerance. The probability that the as-built value falls within the specified tolerance range (i.e., the probability of compliance, P) is then calculated for each parameter, and F_d is calculated as a weighted value of all four probabilities (Figure 6a). Weighting of the individual probabilities of compliance is subjective, and "calibration" is based on experience. F_c is based on evaluation of six parameters (Figure 6b) which represent the impact of blasting, the quality of the excavation and scaling, and residual rockfall hazards. Numerical values within a specified range are assigned to each parameter and cumulated, resulting in a net numerical rating from 0 to 100. This rating is divided by 100 to determine the Fd value. F_d and F_c values are then plotted on a simple chart to determine the overall rating as illustrated on Figure 6c.

Rockfall Hazard Management

Establishing and maintaining sufficient berm width to catch and control structural failures and provide safe access to the slope is important, but bench design may ultimately be dictated by the need to control rockfalls. This is often the case where bench face angles and/or inter-ramp slopes are steep, or where bench heights are high. Observations made during periodic bench inspections can be used to evaluate the effectiveness of the catchment at controlling rockfalls and identify source areas. Sectors where rockfalls are not being adequately controlled can be identified and plotted on a rockfall activity/hazard plan. Periodic reviews of this plan should be conducted to assess the overall effectiveness of rockfall controls and whether or not mitigative measures or modifications to the bench geometry are required. Mitigation could include passive measures such as buffer zones, hazard warnings or temporary sector closures intended to limit exposure. Active mitigation measures could involve construction of impact berms or rockfall fences, supplementary scaling, or installation of draped mesh. Design modifications could include increasing the bench width or flattening the bench face angle, either of which result in a flattening of the inter-ramp slope angle. Where effective rockfall catchment has been lost on multiple benches and the resulting residual risk is deemed to be unacceptable, the only viable option may be to step-in and establish a wide catchment bench.

Parameter	Weight (W)
Berm Wdith (L)	0.3
Bench Face Angle (â)	0.2
Inter-ramp Angle (è)	0.2
Toe Compliance (Ä)	0.3

Design Compliance Factor, F_d = Ó (P_i x W_i)/100

Where: P_i = Probability of compliance for Parameter i

W_i = Weight applied to Parameter i

Figure 6a *- Design Factor*

Parameter	Description/ Rating	Category: Good	Moderate	Poor
Blast-induced cracks (No. of cracks within 10m of crest)	No. of cracks	0-5	5-10	10-15
	Rating	13-10	10-7	7-0
Condition of minor discontinuities	Condition	Minor open joints	Few open joints	Many open, mobilized joints
	Rating	13-10	10-7	7-0
Presence of unstable blocks	Description	Minor unstable blocks (0-2)	Few unstable blocks (3-5)	Many unstable, mobilized blocks
	Rating	23-15	15-11	11-0
Slope Profile Toe Overdigging	Description	Minor overdigging <20%	Moderate overdigging 20-40%	Extensive overdigging >40%
	Rating	16-11	11-8	8-0
Slope Profile Crest Overdigging	Description	Minor overdigging <20%	Moderate overdigging 20-40%	Extensive overdigging >40%
	Rating	16-11	11-8	8-0
Condition of Crest	Description	<1m fracturing or overbreak	1-2m fracturing or overbreak	>2m fracturing or overbreak
	Rating	23-16	16-11	11-0

Condition Factor, F_c = Ó (R_i)/100

Where: R_i = Rating for Parameter i

Figure 6b *- Condition Factor*

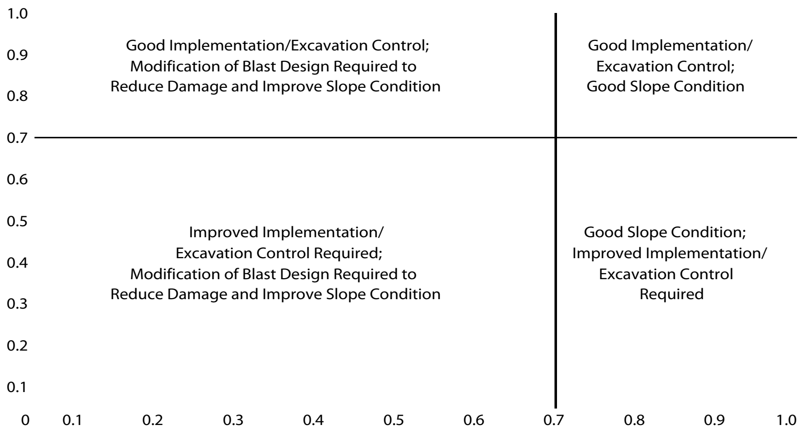

Figure 6c *- Performance rating chart*

Figure 6 *- Composite Bench Performance Rating System (courtesy, Compañia Minera Doña Inéz de Collahuasi S.C.M.)*

A well maintained rockfall activity/hazard plan is a valuable tool that can be used to mitigate risk to personnel and equipment, and plan and prioritize remedial measures. A comprehensive rockfall hazard identification and mapping system was recently developed and in being systematically implemented on a trial basis at the Antamina Mine in Peru (Gilmore et al (8)). Rockfall hazard levels systematically identified throughout the pit using these criteria are displayed on a current mine status plan, such as typically illustrated on Figure 7. This hazard level status plan is posted in key locations to convey the information to mine personnel, and is used to facilitate discussions and directives during safety, operations and planning meetings. Trial implementation of this system at Antamina has been very successful to date.

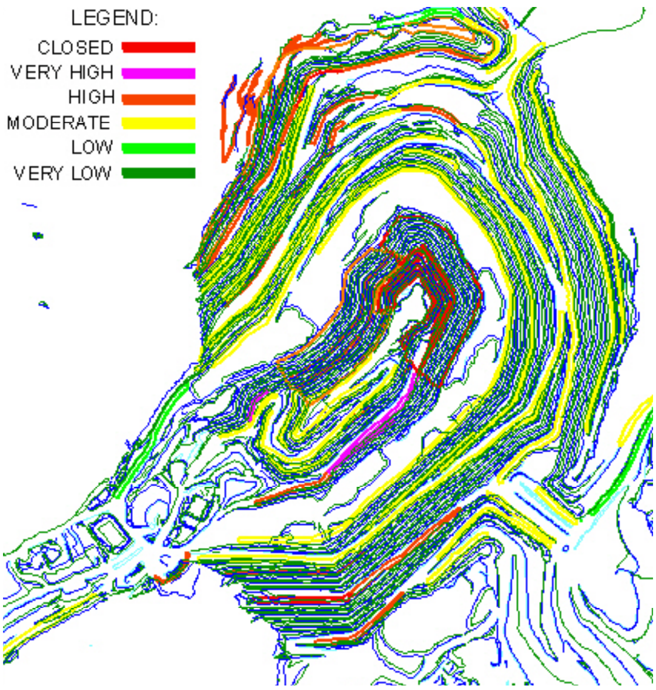

Figure 7 *- Typical Rockfall Hazard Plan (courtesy Compañia Minera Antamina S.A.)*

Personnel working in the pit should be encouraged to report all rockfalls. Significant rockfall events should also be documented, plotted on a plan and captured in a database. Documentation should include information on the date of occurrence, final location, source area, size and shape, vertical and horizontal travel distances, rock type, and other pertinent details. Detailed rockfall documentation data is essential for calibration of analytical rockfall models such as CRSP (Jones et al (9)), Rockfall (RocScience (10)), etc. Models such as these can provide valuable insight into the mechanics of rockfalls and their sensitivity to slope geometry and mitigative measures.

Inter-ramp Slope Geometry

Inter-ramp slope design criteria typically include specification of the inter-ramp slope angle (θ_d) and the maximum slope height between ramps, or planned step-outs (H_i) (Figure 2). Slope performance assessments should include systematic and periodic documentation of as-built inter-ramp slopes to verify that the slope is being mined in compliance with the design. Mine status plans that depict bench toes and crests with reasonable accuracy are usually sufficient for assessing basic inter-ramp design compliance. However, digital topographic models developed using laser scanners, photogrammetry, high resolution aerial photos or satellite images can be used to develop statistically reliable data sets for more detailed analysis using similar techniques as described above for benches. This data can also be used to examine the relationship between inter-ramp slope angle and height, and to differentiate between stable and unstable slope profiles, as illustrated in Figure 8. Where as-built inter-ramp slopes angles or heights are consistently lower than allowed by the design criteria, and slopes are performing well, consideration might be given to increasing θ_d or H_i; conversely, if the slopes are not performing well, reducing θ_d or Hi might be required.

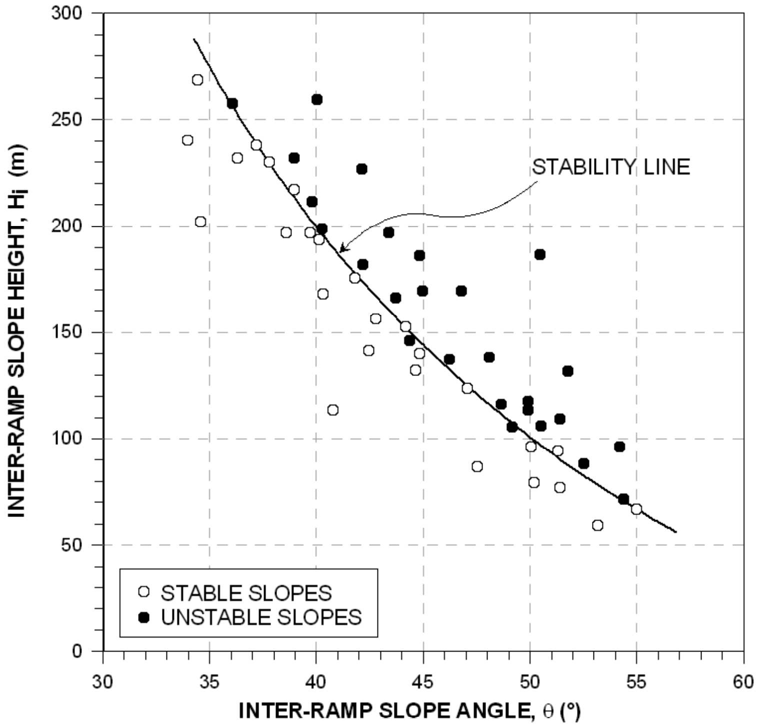

Figure 8 *- Inter-ramp Height vs. Inter-Ramp Slope angle.*

Effectiveness of the Inter-ramp Slope Design

In addition to assessing compliance with the geometric design criteria, slope performance assessments should evaluate the effectiveness of the inter-ramp slope design. Does the design meet expectations in terms of preventing or controlling multi-bench and inter-ramp instability? In some cases inter-ramp slope performance can be evaluated in terms of objective acceptability criteria, such as the frequency or size of multi-bench failures, the cost of cleanup and remedial measures, or the frequency and length of disruptions to production. However, these types of assessments typically require detailed, statistically reliable historical records which are often not available, except at some mature operations. In most cases, it is necessary to apply more subjective criteria, such as qualitative assessments about the overall effectiveness of catchment, the accessibility of the slope, and whether or not any multi-bench failure that do occur are being adequately controlled on the slope.

It is usually easy to identify inter-ramp slope segments that are not performing adequately because they are either too steep or too high. The solution to this type of problem could be to flatten the slope, either by reducing the height of the bench stack, or by increasing the step-out width, both of which negatively impact the stripping ratio or push the toe of the slope off design, reducing the quantity of ore or deferring ore release to a later phase. Suboptimal inter-ramp slope performance where the design is too conservative is more difficult to identify because positive slope performance does not necessarily indicate an inappropriate or overly conservative design. One way to assess opportunities for steepening is to establish trial slopes wherein the inter-ramp slope angles and/or heights are incrementally steeper and/or higher than the design. Such trials are best suited for interim or temporary slopes where the consequences of instability are not significant and can be controlled.

Multi-bench and Inter-ramp Failures

Multi-bench instabilities include failures that involve more than one bench, but which are limited to a single inter-ramp section (see Figure 9).

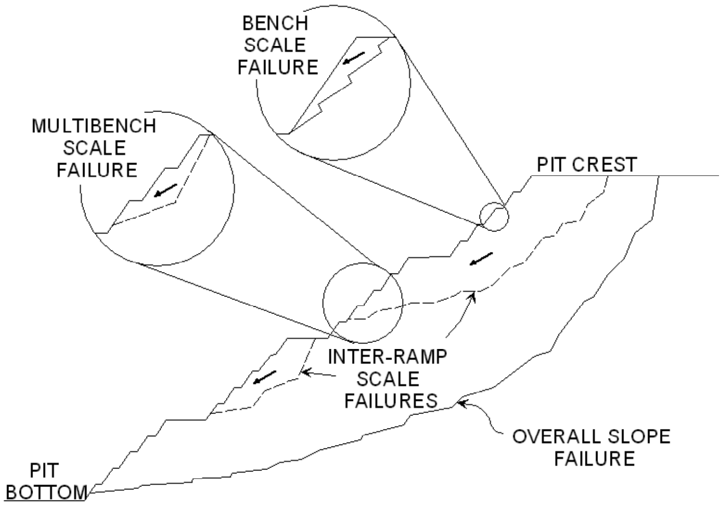

Figure 9 *- Scale of Instabilities*

Depending on the height of the inter-ramp slope, this definition typically includes instabilities that range in size from 10s of metres to a few hundred metres. Because of this order of magnitude range, and the consequent wide range in potential impacts, a one-size-fits-all approach to documentation and back analysis of multi-bench instabilities is inappropriate. Rather, the level of documentation and back analysis needs to be customized depending on the size and potential impact of a given failure. Small scale multi-bench failures involving a few benches that do not impact critical infrastructure might appropriately be considered using the same approach as suggested above for bench-scale failures. Large scale failures involving the full inter-ramp slope height and/or affecting critical haulroads or infrastructure require a much higher level of investigation and study. In addition to basic information identifying the location, date, geometry and type of failure, and the characteristics of any discontinuities involved, documentation of multi-bench failures should include compilation and review of deformation monitoring, bench inspection, blasting and precipitation records. Table 1 is a suggested checklist of things to consider when documenting multi-bench failures.

Depending on their size, the failure mechanism, and the nature of the rock mass, multi-bench instabilities may exhibit precursors to failure that can be recognized, such as developing tension cracks or scarps, accelerating deformation rates or an increase in the frequency or size of rockfalls or raveling. Ideally, monitoring programs will be in place such that any multi-bench failures that might present a significant risk to the mining operation are recognized sufficiently in advance of failure so that effective mitigative measures can be implemented. Good monitoring records also provide a valuable source of information that may help in understanding the failure mechanism and triggering events.

General Information

- Identification number or code
- Location (phase, structural domain, wall, design sector)
- Limits (height, width, depth, volume, mass)
- Date first recognized, failure date
- Initial manifestations (cracking, settlement, heave, rockfalls, raveling)

Survey and Monitoring Data

- Before and after photographs
- Before and after topographic surveys or scans
- Crack maps
- Slope inspection records
- Monitoring plan (instrument locations)
- Movement monitoring records (prisms, extensometers, inclinometers/TDRs, SSR data)
- Piezometer monitoring records
- Dewatering records
- Precipitation records

Geologic Information

- Drillhole locations and logs
- Geologic maps, sections and 3D models (lithology, alteration, structure, mineralization)

- Bench mapping data
- Stereographic projections of structural fabric data
- Structural contour plans of controlling discontinuities

Geotechnical Information

- Slope documentation records
- Geotechnical maps, sections and 3D models
- Discontinuity shear strength criteria
- Rock mass classification information
- Rock mass strength criteria
- Insitu stress conditions

Blasting and Seismic Information

- Design details and dates for recent proximal blasts
- Blast monitoring records
- Blast damage reports or surveys
- Seismic event records

Slope Design and Performance

- Bench and inter-ramp design criteria
- Analytical basis for design
- Slope performance data
- Previous instability history

Assessment of Failure Mechanism

- Nature of deformations (deformation rate, inverse velocity, movement history, triggering mechanisms)
- Structural and kinematic controls
- Rock mass controls
- Results of back analyses

Risk Assessment and Remedial Measures

- Current status (stable, creeping, decelerating, steady state, accelerating)
- Impact on operations (current, future)
- Alternative remedial measures
- Cost-benefit analyses

Table I *- Checklist for Documentation of Multi-Bench Failures*

Stereographic projections, plans, sections and 3D representations that illustrate the geometry of the failure and any structural controls may be useful in understanding the mechanism. For more complex, structurally controlled failure mechanisms, simple planar representations of the key structures may not be adequate, and it may be necessary to develop and interpret detailed structural contour plans of individual discontinuities to appreciate the complexity and 3D component. Before and after photographs and scans can also help in visualizing and quantifying failures.

As for bench-scale failures, back analysis of multi-bench failures can help to calibrate and refine discontinuity shear strength assumptions. Failures that involve a component of shearing through the rock mass may provide unique opportunities to calibrate rock mass shear strength. The type and extent of back analysis will depend on the size and nature of the failure, and the amount and reliability of the documentation data. Simple limit equilibrium analysis techniques may be sufficient for small scale or mechanically simple failures, whereas complex, large failures may require sophisticated numerical modeling. In some cases, multiple approaches may be appropriate to help assess the reliability of a given analysis technique. Regardless of the analysis technique chosen, results should be expressed in terms of sensitivity to key input parameters and compared to previous back analyses to validate and refine critical assumptions. In cases where back analysis reveals significant variations in key shear strength assumptions, or material changes to the underlying geological interpretation, review and revision of the slope design criteria may be necessary.

OVERALL SLOPE PERFORMANCE

Overall slopes are usually limited either by the inter-ramp design criteria, the shape of the orebody, haulroad access or other mine planning considerations, or some combination of these factors. In these cases, it may be sufficient to document as-built overall slope geometries to ensure that they are in compliance with the design, and conduct routine monitoring to warn of unanticipated deformations, geological complications or developing adverse pore pressures. However, in cases where adverse structural conditions are present or the rock mass is weak, overall slope stability issues may also control design. In these situations, overall slope performance evaluation is more critical and may require specific instrumentation, more vigilant monitoring, and supplementary investigations to confirm the design as the slope is developed.

Deformation and Pore Pressure Response

To objectively evaluate overall slope performance based on the results of instrumentation monitoring, it is important to consider the expected response of the slope to mining. The expected response will depend on the geology, the nature of the rock mass, the height and steepness of the slope, and initial pore pressure conditions. Initial predictions of expected response should be prepared during the design stage of the project. For modest slopes, these initial predictions might be based simply on experience with similar slopes or simple modeling. For large slopes or slopes in complicated geological environments, sophisticated numerical modeling may be required. Such models typically require detailed calibration based on documented response over time. Regardless of the approach used to estimate expected response, adjustments will be required as the slope is developed to reflect actual, documented slope behaviour.

Hydrogeological and Geotechnical Sections and Monitoring Plans

Maintaining detailed, representative hydrogeological and geotechnical sections through each of the main pit slopes is fundamental. These sections can be used to compare the as-built slope geometry to the overall slope design criteria, and to qualitatively evaluate the potential impact of variances. Key instruments and monitoring results (prisms, inclinometers, piezometers) should be shown on these sections. Monitoring results should also be shown on appropriately scaled plans or 3D visualizations so that the locations and extents of any zones of abnormal or unexpected response can be identified early. Such plans might illustrate total or component movement vectors, incremental or cumulative deformation magnitudes or rates, piezometric pressure contours or pore pressure dissipation rates, distribution of micoseismic events, etc.

Photographic Records

Maintaining a periodic photographic record of the slope as it develops is also strongly advised. Comparison of photographs of overall slopes taken periodically from strategic vantage points can reveal subtle variations in slope behaviour over time that may not be apparent in other types of monitoring. Individual and time series photographs can also aid in communicating specific performance issues. Targeted video surveillance may also be useful in specific cases where instability is anticipated within a reasonably narrow time frame. Some operations now provide continuous video surveillance of pit walls.

Large Scale Slope Instabilities

Large scale slope instabilities that involve multiple inter-ramp slope segments or the overall slope can threaten the economic or social viability of a mine, and in rare cases may result in fatalities. In this context, it could be argued that the most important objective of any ongoing slope performance assessment program ought to be early recognition of developing large scale instability. In such cases, early recognition is vital so that mitigative measures can be designed and implemented in time, and human and economic risks can be appropriately managed.

In the unfortunate event that large scale instability does develop, documenting its progression is key to understanding the failure mechanism and developing mitigative or remedial plans. Detailed monitoring and photographic records are critical for reliable numerical calibration and validation of stability analysis models that are needed to develop rational response plans. Understanding the mode of failure and triggering mechanisms may require detailed analysis of the mining sequence. The impact of blasting, pore pressures, in situ stresses and other factors may also need to be considered, and supplementary investigations may be needed to fill knowledge gaps and validate models. In short, understanding, predicting and managing potential large scale instabilities, and developing effective mitigative and remedial plans, requires a comprehensive, holistic approach that considers all factors and is unique to each situation. Specialist advice and external reviews are strongly advised to ensure that all of the appropriate steps are taken when dealing with large scale instabilities.

Slope Depressurization and Pit Dewatering

The design of most large slopes requires at least a general understanding of the potential impact of groundwater on the mining operations. Large slopes may be sensitive to piezometric pressures, and designs may anticipate natural or enhanced depressurization of the walls. In these cases it is important to monitor changes in piezometric pressures as the slopes develop to ensure that depressurization targets are met. If targets are not being achieved, planned depressurization efforts may have to be advanced or increased, or slopes may have to flattened to maintain stability. Provided the groundwater flow system is reasonably well understood, and the slopes are appropriate instrumented with piezometers, depressurization rates can be tracked and results plotted on plans and/or sections and compared to projections and targets.

In some open pits, pit bottom sumps with modest pumps are all that is required to maintain a dry excavation. However, most operations require at least some form of in-pit or pit rim well dewatering. Installation of deep dewatering wells can be very expensive, and delaying their installation for as long as possible is usually attractive. This approach requires careful monitoring of groundwater levels to ensure that wells are installed and replaced as needed to keep up with mining. Monitoring usually includes sealed piezometers and open standpipes, as well as observations of seeps and local ponding. Hydrographs that track groundwater levels and dewatering rates over time and in relation to pit development, in combination with appropriate plans, sections or 3D representations showing the current water table or piezometric surface contours and profiles, provide convenient media for evaluating performance.

SUMMARY AND CONCLUSIONS

Open pit slope design is an iterative, often highly empirical process whereby slope designs are developed based on the available information, implemented according to the established criteria, systematically documented and evaluated, and modified in accordance with observed performance. Slope performance assessments must be customized to suit the unique environment and available resources of each operation, and should include slope documentation and monitoring.

Slope documentation programs should provide the information needed to progressively validate and refine the geotechnical models, and in particular, the underlying geological model. Documentation needs to address each of the key scale components of the design: benches, inter-ramp slopes and overall slopes.

Our ability to model and understand the mechanics of slope stability has advanced dramatically since the introduction of modern pit slope design methodologies in the 1970s. However, despite our best efforts, large scale slope instabilities still occur. In most cases these involve structures or mechanisms that were unanticipated or misunderstood, often because the underlying interpretive geological model was incomplete or incorrect. Consequently, comprehensive, rigorous slope monitoring remains the most important tool for assessing overall slope performance.

Where possible, slope performance should be evaluated objectively against expected responses and clear acceptability criteria. However, due to the complexity of the geologic environment and mining process, the slope design and performance evaluation cycle will continue to involve subjective judgment. In this context, there is no substitute for experience and continuity.

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