Risk Management – Geomechanics Application for Open Pit Slope Design and Performance

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Abstract

The assessment and management of risk in the mining industry is becoming an integral component of project development from the conceptual design level, through detailed design for construction, to sustaining operations. Consequences of an open pit slope failure can have significant safety and/or economic impacts, and hence the slope designs can form a significant part of the risk assessment for an open pit mine.

This document presents an overview of risk management applied to open pit mining operations, with particular focus on geomechanics performance management. Risk management may be generally defined as the culture, processes and structures directed towards realizing potential opportunities while managing adverse effects. The process contains an analysis component for identifying and assessing risks, and an evaluation component applied to controlling and monitoring risks. Risk assessment methods are typically categorized as qualitative, semi-quantitative and quantitative. A mining company's safety and risk management culture improves and matures through increased employee awareness of risk. Collaborative exchanges involving the development and performance of risk assessments and resulting evolution of improving and sustaining management practices and procedures are part of this process.

The level of uncertainty in any design involving the excavation of earth materials must be recognized at each stage of project development. It should be factored into the analytical process used to formulate the design criteria and recorded in terms of the assessment of confidence levels.

The principal goals of a geomechanics management program are achieved with an effective performance monitoring system, developed jointly with the mine operators. To maintain a consistent high standard of geomechanics management, many companies require that their operations develop comprehensive ground control, or geomechanics management plans (GMPs). A GMP should encourage the application of current knowledge, methodology, instrumentation and ground support to the practical solution of geotechnical challenges specific to the operation for which it is developed. The development and implementation of GMPs are increasingly becoming a part of the corporate governance process in the mining industry.

INTRODUCTION

Mining is considered to be a high risk business in terms of both safety and economics. There is always the possibility that an excavated slope may not perform as predicted and could fail with significant and even catastrophic results. For such compelling reasons, risk management is rapidly becoming accepted as standard procedure in the mining industry. Formal procedures of risk assessment have been developed for a wide range of industries in the last few decades, including the aviation, nuclear and military industries, but only more recently have they been adapted for mining.

The mining industry has advanced significantly and positively in the subject of safety awareness and safety culture is now a key phrase in all aspects of mining practice. However, even with the development and utilization of best practices in corporate governance and the implementation of a robust risk management system, low probability/high consequence events like slope instabilities may continue to occur in both small and large open pits.

Risk is defined simply in the Worldbook Dictionary (1) as "a chance of harm, or loss"; and even more simply as "danger". In the Guidelines for Open Pit Slope Design (Guidelines (2)), risk is defined as the chance of something happening that will have an impact on objectives. Risk is often defined quantitatively in industry practice as the probability of failure (PoF) times the consequence of failure, or simply:

Risk = PoF x Consequence of the event

Considerable recent literature is available on the subject of Risk Management. Suggested reference material is summarized in Chapter 13 of the Guidelines.

The objective of this paper is to provide a review of the standard components of risk management applied to geomechanics aspects of open pit slope design and performance, and to present these in a practical context for the operating stage of mine development. This paper begins with a review of geotechnical considerations in the context of the risk management process and assessment methodologies. The risk evaluation process and development of mitigation options and control measures are then examined. The requirement for slope performance monitoring during mine development and operations is then described as an essential component in implementing the risk management plan. This is followed by a discussion of the development of a geomechanics management plan. Risk management program monitoring and reassessment are also summarized.

RISK MANAGEMENT PROCESS

Risk management is defined in the Guidelines as the culture, processes and structures directed towards realizing potential opportunities while managing adverse effects. The AS/NZ 4360: 2440 risk management process (3), shown in Figure 1, contains assessment components that will be familiar to many practitioners in the mining industry. The risk management process shown contains: 1) a risk analysis component that includes the elements for establishing the context, identifying risks and analyzing risks, and 2) a risk evaluation component that includes the elements for evaluating risks, treating risks, and monitoring and reviewing. For the risk management process to be realistic, credible and useful, it must be periodically reviewed, communicated effectively with all stakeholders, and adjusted as needed to safely optimize achievement of the objective.

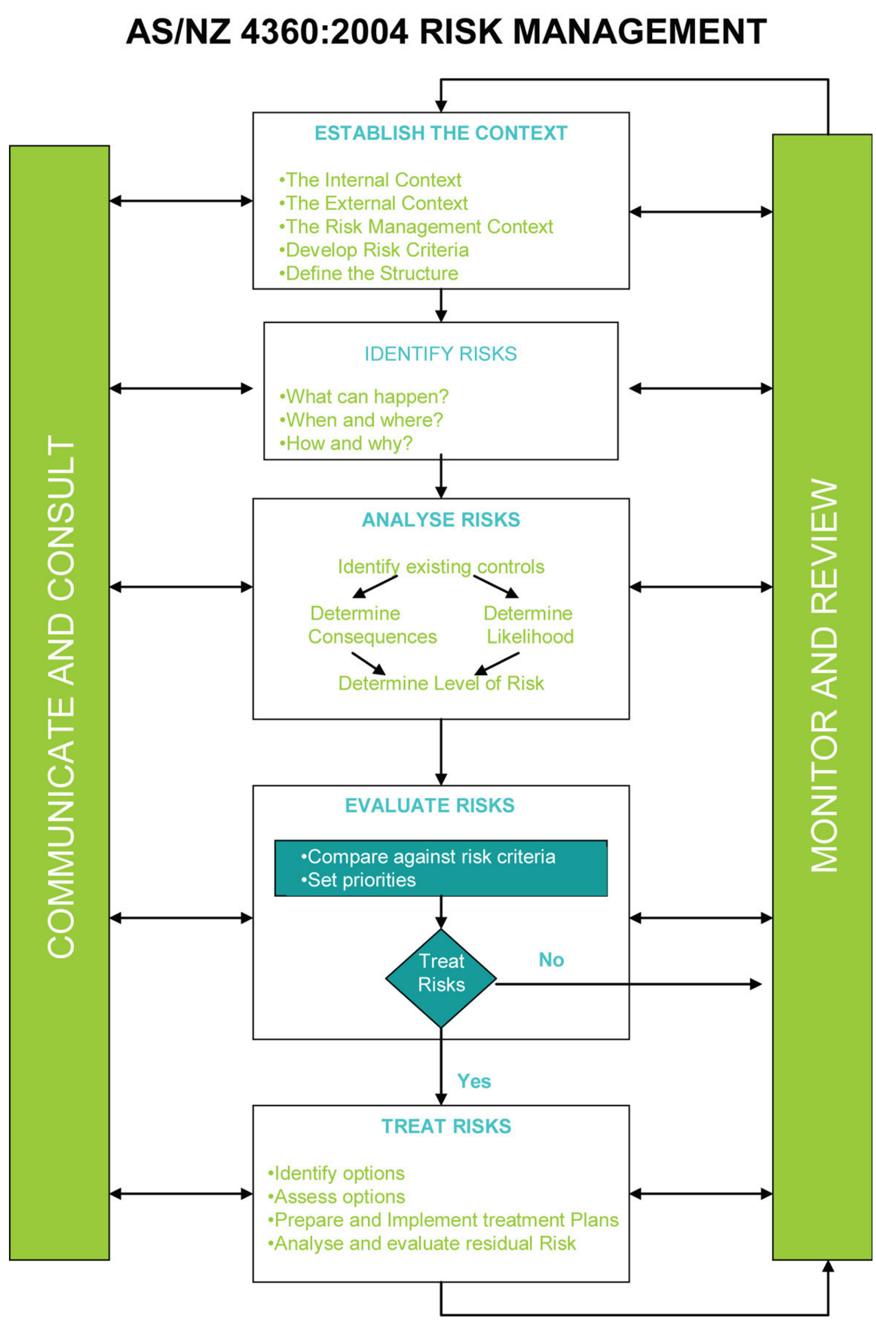


Figure 1 *- Risk Management Process*

Mining is inherently a risky business with a legacy of economic failure and loss of life. As a consequence, the increasing utilization of formal and systematic risk assessment and management procedures in the mining industry are positive developments. Increasingly, mining companies and mining operations have corporate risk management requirements and procedures that in many cases exceed regulatory requirements. These cover aspects of corporate governance, business continuity, exploration, mine design, development and processing operations. The assessment and management of risk are becoming integral components of project development from the conceptual design level through to design, construction and sustaining operations. A company's safety and risk management culture improves and matures by increasing employee awareness of risk through collaborative exchanges involving the development and performance of risk assessments and the resulting evolution of improving and sustaining management practices and procedures.

GEOTECHNICAL RISK CONSIDERATION

Overview

The first four steps in assessing geotechnical risk associated with large open pit slopes are interpreted in the Guidelines as follows.

- Establishing the external context of the relationship between the mining operation and the environment in which it exists.
- Establishing the internal context, including the objectives of the operation, strategies developed to achieve them, and determination of risk tolerance.
- Establishing the risk management context sets the scope and objectives of the risk management process, which in the case of slope design is directed at maximizing safety while optimizing economic return.
- Developing risk criteria using an operationally holistic approach that is applied to the geotechnical risk that is to be evaluated.

Geotechnical risks associated with design and development of open pit slopes arise primarily from the uncertainties inherent in the characterization of the rock mass and its components; including the engineering/structural geology, material properties and groundwater conditions, collectively referred to as the geotechnical model. Design confidence in the geotechnical model improves as a project advances through the five levels of design and operational development, defined in the Guidelines (Chapter 8). This is a function of the increasing amount of factual data that becomes available through exploration, refinement of the geotechnical model used for analysis and eventual excavation experience. Development and refinement of risk assessments and risk management plans can thus be advanced accordingly as an integral part of the process.

Risk Based Design Approach

Using a risk based geotechnical slope design approach should be considered in addition to conventional deterministic approaches, the accuracy of which can only be validated through applied excavation experience. The approach involves probabilistically determined likelihoods and consequences of slope failures of various proportions. Management has the opportunity, using this approach, to determine acceptable levels of safety and economic risk. It quantifies the levels of risk associated with optional pit design configurations, or development sequence phases, and provides a basis for the development of slope management plans. The process also involves quantification of the economic value added and safety risks imposed by increasing the level of design imposed risks.

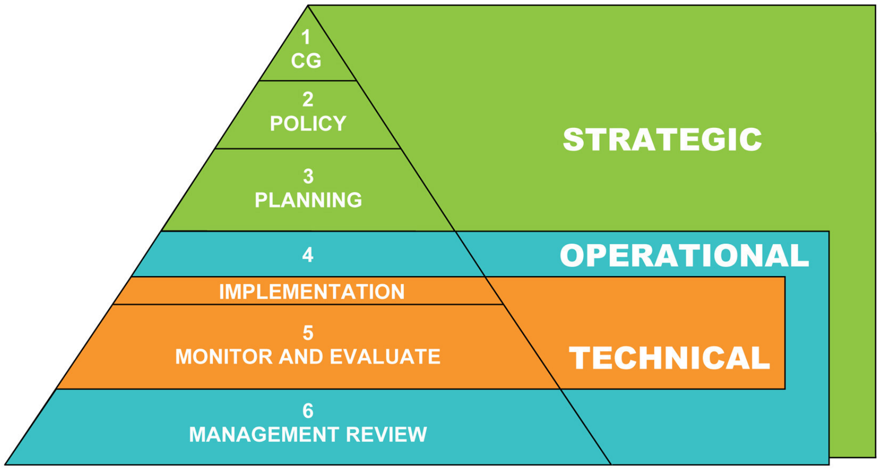
A probability driven risk based design should also be validated for accuracy through relevant site specific excavation experience. Slope design criteria should be fixed through consideration of both accepted industry standards and company and specific project risk tolerance. The advantages of a risk based design approach, such as provided by examples from Steffen et al. (4, 5), Tapia et al. (6), should be explored for purposes of optimizing (balance of safest and steepest) slope designs and maximizing economic return, particularly as operational experience increases.

Risk management methodology

The methodology for managing the risk of open pit slope failure is shown diagrammatically in Figure 2. It shows how strategic, operational and technical components of risk assessment relate to the corporate governance, policy, planning, implementation, monitoring and review levels, or hierarchy of the overall risk management process. Particular focus at the operational stage of mine development is directed to the Implementation, Monitoring and Evaluation components of the risk management process. Emphasis is placed on the operational risk management (4.2), monitor and measurement (5.1), and investigation, corrective action and preventative action (5.2) components. Principal goals of an effective geomechanics management program are achieved with an effective performance monitoring system and where mine operators are fully aware of the potential hazards. The overall risk management methodology is subsequently revisited in a following discussion of the development of Geomechanics Management Plans.

RISK ASSESSMENT METHODOLOGY

Risk assessment is defined in the Guidelines as the overall process of risk identification, analysis and evaluation. Risk assessment methods are typically categorized as qualitative, semi-quantitative and quantitative. Descriptions of these three methods of assessing risk are provided in Chapter 13 of the Guidelines. The following comments generally apply for these methods.



1	**Corporate Governance** – Establish the overarching Risk or Safety Management System.
2	**Policy** – Company directed policy on occupational health and safety (OHS) and acceptance criteria for geotechnical considerations in the life of the open pit
3	**Planning** – covering Stages 1-5 (Conceptual through Operations) 3.1 Risk management and generic business continuity management 3.2 Legal requirements and compliance with standards 3.3 Business objectives, targets, plans, risk benefit analysis, geotechnical model, pit design.
4	**Implementation** of plans, procedures, standard operating procedures (SOPs) and records at the design, operational and closure/transitional levels 4.1 Organisational structure, roles and responsibility 4.2 Operational risk management – geotechnical model, pit design, implementation, slope management plan, geotechnical procedures, eg, mapping and monitoring 4.3 Business continuity management 4.4 Consultation, communication and reporting 4.3 Training and competency 4.5 Documentation and data control
5	**Monitor and Evaluate** – stability management, mine to design, design performance 5.1 Monitoring and measurement 5.2 Incident investigation, corrective action and preventative action 5.3 Records and record management 5.4 Audit - internal and external
6	**Management Review**

Figure 2 *- General methodology for managing geotechnical risk potential applied to open pit mining projects.*

- Qualitative methods are useful in initial project development to identify risks requiring more detailed analysis, or where factual data and experience are inadequate for quantitative analysis.
- Semi-quantitative methods can weight qualitative descriptions of likelihoods and/or consequences of potential events to produce more reliable risk rankings than qualitative methods; to be realistic and meaningful, these methods require the existence of a reasonable amount of reliable factual data. This approach may be useful in ranking and prioritizing risks elements.
- Quantitative methods use numerical values, or estimates, to develop a measure of risk, based on assessment of likelihood and consequence. This approach requires a high level of supporting reliable factual data. As such, this approach provides the clearest and most useful outcomes of a risk assessment.

Although risk assessment could be conducted in more detail, comprehensiveness is more important than precision at the initial design stage. Precision will be developed in the detailed design and operating stages of mine development, when results from more detailed site investigations and mining experience become available. Otherwise, a great deal of unnecessary effort could be spent on study elements that are highly speculative, or could become insignificant, or irrelevant.

For the development of phased expansion slope designs for mature large open pits, the quantitative method is the most useful and reliable method for the assessment of risk exposure. This approach can be used to filter out slope design options to develop an optimized solution, and identify data gaps for further resolution that can be used to further reduce risk exposure. A quantitative risk assessment should also be used in the financial decision process for defining, for example, whether a steeper cut with ground support is more economical than an unsupported flatter one.

Risk Identification

The comprehensive identification of risk elements using a well structured systematic process is vital because risks not identified may be excluded from further analysis. This process is facilitated by recognizing hazards and risks common to many open pit mining operations, including:

- Geology risk that may include a poorly defined geology model with a lower than expected level of confidence; errors resulting from insufficient, or biased drilling, insufficient or biased data and interpretive errors;

- Structure risk resulting from the exposure of previously unidentified geological structure and lower than expected levels of confidence in the structural geological model, resulting from random and/or systematic error in the core orientation process, inaccurate structure mapping and/or interpretation, insufficient consideration of the rock mass fabric (jointing, foliation), and limitations of analytical tools to assess structural failure potential;
- Rock mass risk resulting from errors in laboratory testing (including non-representative samples), or back analysis assessment of the shear strength of a critical structure, and/or insufficient or unreliable factual rock mass data, contributing to an inadequate geotechnical model; errors in data collection that can include data bias and lack of experience, which can include non-compliance with established procedures;
- Hydrogeology risk resulting from an inaccurate assessment of the groundwater pressure distribution, inability to achieve depressurization targets, overly optimistic assessment of the ability to depressurize low permeability ground, in-sufficient measures taken to implement and maintain the dewatering system necessary to achieve depressurization targets, and designs that have not adequately accounted for transient storm events;
- Operational performance risk resulting from poor perimeter blasting practice, over-excavation of rock catchment berms, inadequate surface water management that permits ponding and infiltration to occur, and inadequate mine dewatering system;
- Seismic Events potential in certain environments;
- In-situ stresses potential in certain environments, geological conditions and pit geometries.

A comprehensive risk register should be developed and maintained throughout the life cycle of the mining operation. Each risk element entered should include a list of its potential causes, a risk rating, and what controls exist or are proposed to eliminate or control the risk within a tolerable limit. The risk register should also identify the safety or business objectives that may be affected. Periodic reviews and updating of the risk register should be done, such as for each stage of project development and when a process change occurs. It is suggested that the risk register be reviewed and updated at least yearly during the mine development stage, or as additional data and investigations become available to justify the review.

Risk Analysis

Risk Analysis is defined by the Guidelines as the systematic process of developing an understanding of the nature of, and to deduce the level of each risk. Results are used to identify those risks that require attention, and to develop cost effective remediation strategies. Risk analysis involves consideration of the sources of risk, the likelihood of occurrence and the potential consequences. The analyses, or risk assessment methods as defined above, may be qualitative, semi-quantitative, or quantitative.

A preliminary quantitative analysis may be conducted to identify risks requiring further detailed assessment, and to identify low-impact risks that can be eliminated from further analysis. However, risks that are excluded from further analysis should be documented in the risk register as a record of their consideration (2).

Sources of geotechnical risk can occur at the bench scale, inter-ramp and overall slope scales. Consequences of failure can have safety and/or economic impacts on the mining operation. These consequences include (adapted from Tapia et al. (6)):

- injury or fatalities to personnel;
- damage to equipment;
- economic impact on production;
- force majeure;
- industrial action (regulatory, resulting in production loss);
- adverse public and stakeholder relations.
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Details of the various methods for risk analysis are summarized in the Guidelines, including suggested references. Risk assessments that are to be performed at mature operations, and/or those with excavation experience (defined as Levels 4 and 5 in the Guidelines), should apply semi-quantitative or quantitative approaches wherever possible. It should be noted, however, that not all risk assessment tools will be effective for assessing the potential for geotechnical hazards where the causes of risk and the required controls are relatively obvious.

Data Uncertainty

The range of existing factual data available and their application in the development of interpretive models, especially in the context of understanding the geological environment of a mining project, will result in the development of uncertainty in the risk assessment process. The level of geotechnical uncertainty decreases as more data, eventually including data and monitoring records derived from excavation experience, become available as the project develops.

Inherent uncertainty must be recognized and recorded at each stage of the analysis to assist in the assessment of confidence levels. The level of uncertainty in any design involving the excavation of earth materials should be factored into the design criteria. Generally, it might be expected that the higher the level of uncertainty with the data, interpretive models, and assumptions used in analyzing the consequences and likelihoods of events, the more conservative should be the decision-making process and the risk acceptance criteria.

In this context, the reader is encouraged to examine relevant details in Chapter 8 of the Guidelines, including the summary of geotechnical effort and target levels of data confidence in Table 8.1.

Risk Evaluation

The risk evaluation process involves comparison of the level of risk determined with criteria established in the context of the risk management process developed for the project. The purpose of risk evaluation is to use the outcomes of risk analysis to decide which risks require treatment and the associated treatment process. Identified risks are then evaluated relative to the acceptance criteria for each established type of risk. Details of this approach, including the overall risk evaluation process, are summarized in Chapter 9 of the Guidelines. The risk evaluation process should be repeated for each level of project development, or when acceptance criteria are refined, or re-defined by the operation.

Risk Matrices

The outcome of a qualitative risk assessment is commonly presented as a Risk Matrix. Risk matrices are useful as a means of communicating the results of a risk assessment exercise that may be qualitatively or semi-quantitatively derived. In the case of assessing open pit slope failure potential, risk matrices would usually be developed to assess both personnel safety and economic consequences of particular risks.

Table 1 (adapted from the Guidelines) shows an example of a simplified qualitative risk matrix. The likelihood of a risk event is plotted vertically on a scale of A (high) to E (low) and the consequence, or impact, is plotted horizontally from insignificant to catastrophic to create a 5 x 5 matrix. Qualitative descriptions at each level of consequence and likelihood are determined by the mine operator and the possible likelihood – consequence combinations are assigned qualitative levels of risk from which limits of acceptability can be defined in a consistent manner. Escalation of risk and implications of risk tolerance are usually denoted by color. It should be noted that a given level of risk acceptance is not intended to infer specific acceptance criteria in relation to personnel injury, or environmental damage. Rather, the method is intended to identify those risks that require further examination. Measures that are developed to control or reduce risk likelihood and/or consequences from unacceptable to tolerable levels may not eliminate the risk. In this case, the resulting residual risks should be documented in the risk register.

Consequences for personal injury and economic impact

Level	Descriptor	Example of Description
1	Insignificant	Minor injury; < 1% cost impact (variance to budget)
2	Minor	Medical treatment; 1-2% cost impact
3	Moderate	Lost time injury/illness; 2-5% cost impact
4	Major	Extensive injuries / permanent disability; 5-10% cost impact
5	Catastrophic	Fatality; > 10% cost impact

Qualitative measures of likelihood

Level	Descriptor	Description
A	Almost Certain	The event will occur (90-100% probability)
B	Expected	Will occur in most circumstances (55-90% probability)
C	Likely	Could occur (30-55% probability)
D	Unlikely	May occur at some time (5-30% probability)
E	Rare	May occur in exceptional circumstances (<5% probability)

Qualitative risk matrix

Likelihood	Consequences				
	Insignificant	Minor	Moderate	Major	Catastrophic
A	H	H	E	E	E
B	M	H	H	E	E
C	L	M	H	E	E
D	L	L	M	H	E
E	L	L	M	H	H

E: Extreme risk: Immediate action required; unacceptable risk
H: High risk: Senior management attention required; unacceptable risk without action
M: Moderate risk: Management responsibility; acceptable with control measures
L: Low risk: Manage with routine procedures; acceptable risk

Table 1 *- Example of a qualitative risk assessment applied to personal safety and economic impact.*

RISK MITIGATION

Risk mitigation involves the identification of options for treating risks before they generate unwanted events, assessing those options, and preparing and implementing treatment plans. Examples of mitigative options for treating geotechnical risks include the following:

- Avoiding the risk by not starting or continuing the activity that may contribute to an unwanted event;
- Changing the likelihood that an unwanted event may occur by means of a mitigative design change;
- Changing the consequences of an unwanted event to reduce the extent of injuries, or economic loss;
- Sharing the risk with other stakeholders through contractual arrangements, insurance and structural (business) arrangements;
- Accepting the risk and develop means, such as an aggressive program of performance monitoring and continual assessment and reporting, to manage it.

Mitigative, or control measures are implemented to reduce an inherent or initial risk. The initial risk is then reassessed with the control measures in place to determine the residual risk. This process of adding control measures and reassessing risk can be carried out a number of times to reduce the residual risk until it satisfies corporate acceptance criteria. Risk evaluation reviews should be conducted at regular intervals.

It is common practice to require that unacceptable risks be eliminated or controlled. It is likewise important to reassess the risks with control measures in place to determine if the residual risks are acceptable. The resolution of control measures determined to reduce a risk to a tolerable level is often subjective and can become the subject of debate. In this context, it is important to highlight the level of uncertainty associated with the new residual risk ranking. This information is generally communicated to management in the context of a mitigative mine plan.

Geotechnical Control Measures

Control measures for geotechnical risks, at the implementation level of project development, commonly include the following (adapted from Joy and Griffiths (7)):

- Accept a more conservative slope design (flatten slope angles) – caution is that this measure does not always reduce the risk;
- Dewatering system implemented to depressurize the slope;
- Leave a buttress at the bottom of the slope;
- Reduce the extraction rate, that may be dictated by evaluation of slope movement rates;
- Increase the rate of mine dewatering, or delay mining until slope depressurization targets are achieved;
- Allow a settling period after blasting;
- Develop geomechanics management plans, including evacuation procedures;
- Install ground support, including rockfall catch fences;
- Increase the width of catch berms;
- Don't mine.

Table 2 summarizes common geotechnical performance monitoring and control measures into three hazard, or risk categories. Geotechnical control measures summarized above are described in detail in Chapters 10, 11 and 12 in the Guidelines.

	Hazard / Risk	Control Measures
1	**Detect slope movement**	Slope monitoring, including reflective prisms and/or radar; mapping, extensometers, inclinometers, piezometers
2	**Reduce impact of rock falls**	Increase berm width, catch fences, reduce slope angle, rock and/or mud containment windrows on catch berms and at base of slope, ground support – mesh and anchors
3	**Control slope movement**	Dewatering/depressurization, good blasting, audit exposure against mine design, rock buttresses

Table 2 *- Common open pit slope geotechnical performance monitoring and control measures.*

Mitigation Plans

The results of the risk assessment, resulting control measures and their likely effects on performance are communicated in the context of a mitigation plan. It would be appropriate at this stage that the mitigation plan be incorporated in the slope management plans, which in course may be incorporated into the broader geotechnical management plan for the operation. Slope performance monitoring at the operational stage of mine development will form a central role in the implementation of these plans. Chapter 13 of the Guidelines provides a detailed summary of geotechnical management activities during the design, construction, operation and closure phases of mine development.

SLOPE PERFORMANCE MONITORING

Definition, Value and Challenge

Performance monitoring is a critical component of the implementation of a mining operation's risk management plan. Field observations, including quantitative measurements obtained by field instrumentation, provide the means by which the geotechnical engineer can evaluate slope performance and mine operations can execute the work with safety and economy. Thus, there is a vital requirement of the mine operator for geotechnical instrumentation, and more than a casual knowledge of how it works and the value of the information that it provides. The value of instrumentation is that it can be used to detect the onset of instability, often before it is detected by visual observation. If evidence of instability appears during or after excavation activities, monitoring data can be used to define the characteristics of instability, thus permitting the selection of an appropriate corrective remedy.

Monitoring systems usually measure ground movement, but can also measure stresses, strains, settlement, blast vibration, groundwater pressures and flows. Technology is constantly improving in terms of measurement precision and accuracy, data presentation, analysis and communication. The challenge for the geotechnical engineer is to determine and implement the type and range of instrumentation needed to assess site specific ground conditions, maintain equipment for high availability and reliability performance, and timely interpretation of monitoring records.

The ability of experienced geotechnical engineers to evaluate the implications of ground movement in almost any mining environment has matured to a high level in recent years. There are numerous examples in the literature. For example, Zavodni (8) compiled guidance for slope instability prediction based on numerous case histories of large slope failures in a variety of geological environments. Highwall performance prediction, based on assessment of strain magnitude, rock mass quality and inferred instability mechanisms experienced at several operations are further examined by Brox and Newcomen (9). The inverse velocity method (Fukuzono (10); Rose (11)) is indicated to be a reliable method for predicting the timing of large and small slope failure events in a wide variety of geological environments. In one documented case history, the inverse-velocity method was used to recognize the onset of instability and for the prediction of the timing of a potential large slope failure. Timely recognition of interpretive results allowed the operation to implement remedial control measures to mitigate the slope failure.

Implementing Risk Management for Operations

The economic viability of a mineral resource that is potentially minable by open pit methods often depends to a significant degree on the slope angles. As a consequence, there is usually significant pressure on the mine design team to generate plans with slopes that will be at the limit of risk tolerance, including design of steep slopes with little operational flexibility. Mine geotechnical personnel, or technical specialists, are therefore charged and challenged with the responsibility to develop slopes as steep as practical, and at the same time conform to design standards and safety criteria. However, the technical specialists, who tend to be risk averse, may be challenged to justify their recommendations; this can ultimately lead to the acceptance of designs that have unresolved uncertainties, or undefined risk.

Based on likelihoods determined from the risk evaluation process, a risk management plan can be established for each risk element identified. The plan should include a relevant performance monitoring program, trigger levels, surface and groundwater controls and blast controls. Geotechnical hazard assessments can be carried out in the feasibility, detailed design and operating stages. However, it is in the operating stage that practical risk control plans for each identified risk are prepared and the appropriate risk management plans developed. Once an open pit mine is in operation, a quantitative risk assessment should be performed to establish the compliance criteria (including threshold values for performance monitoring instrumentation) and, through monitoring as the mining progresses, refine the threshold values.

An important element of risk mitigation plans includes a planned course of action to be taken in the event that specified warning levels are exceeded, or specific events occur. Such contingency, or trigger action response plans (TARPs) should insure that:

- each identified high level risk should have a defined trigger that initiates a plan of action;
- all employees potentially affected by triggers know how to respond to them;
- responsibilities and accountabilities are clearly defined to carry out the plan with minimal delay;
- the pit and/or surface facilities are evacuated in a timely, controlled and efficient manner;
- an effective mechanism is in place to ensure rapid notification of all relevant employee groups and management.

The roles and responsibilities of key personnel, including the Mine Manager, Pit Superintendent and Geotechnical Engineer, should be clearly defined. The plan must establish a series of responses appropriate to escalating levels that exceed compliance criteria.

GEOMECHANICS MANAGEMENT PLANS

Rock slope failures, the mitigative measures necessary to prevent them, or the remedial works required to repair them, can come at considerable cost to the operation. In order to minimize the amount of waste rock that must be excavated to recover the ore body, the ultimate slopes are usually cut to the steepest possible angle. The risks associated with this design and implementation approach justify a slope and risk management system that includes a well thought out process to ensure that mine plans are properly implemented and operationally sustained.

Various approaches or practices have been adopted in large open pit mining operations to address the requirements of the project to optimize their slope designs and at the same time conform to design standards, safety criteria and limits of risk tolerance. To maintain a consistent high standard of geomechanics management, many companies now require that their operations develop, or update, comprehensive ground control or geomechanics management plans (GMPs).

GMPs should encourage the application of current geotechnical knowledge, methodology, instrumentation, and ground support to the practical solution of geotechnical challenges specific to the operation for which it is developed. The GMPs should be: 1) oriented for consistency, compliance and flexibility with overall company objectives and; 2) support and be in alignment with corporate safety programs and targets.

The suggested outline for a GMP could include the following:

- Definition of roles and responsibilities for development, implementation and maintenance of the GMP;
- Geology and geotechnical models, including the process of continuing collection, compilation and interpretation of factual data and model reconciliation;
- Slope design criteria for the current stage of the project; risk assessment and risk management;
- Implementation requirements for the slope designs during the operating stage;
- Geotechnical considerations for mine closure;
- Geotechnical hazard identification, response and communication;
- Management review.

Design, environmental and closure components, together with operational management of waste rock facilities, may also be incorporated in the GMP. Process facilities, such as tailings and/or heap leach facilities, are assumed to have separate "Operations Manuals"; thus they are not included in this context.

GMPs at the operational stage of the mining operation should also describe the following implementation requirements:

- Excavation techniques and diggability for the various material types that will be exposed in the open pit, including overburden, weathered and altered zones and bedrock;
- Surface water control, with emphasis on slope protection for erodible units, such as saprolite and poorly-cemented sediments; surface water diversion ditches and collection/storage systems and sumps;
- Controlled blasting, including perimeter blast designs necessary to achieve the slope design configurations and ensure bench integrity;
- Clean-up of bench faces and benches (berms), including scaling, control of back-break and crest damage and removal of loose rocks from berms;
- Rockfall protection, including measures for addressing loose material that remains, or develops on the highwalls;
- Dewatering, including slope depressurization and groundwater management for stability control; horizontal drains, pumping wells, drainage galleries, collection systems and sumps; addressing permafrost considerations;
- Use of ground support, including determination of appropriate applications, selection of ground support systems and ground support installation procedures;
- Monitoring program, including assessment of available slope performance monitoring methods, development and application of appropriate and necessary monitoring systems; frequency of monitoring, data interpretation and reporting.

The development and implementation of GMPs are becoming increasingly accepted as a vital and best practice approach to the safe and profitable development of mining operations, and are increasingly becoming a part of the corporate governance process in the mining industry. They provide a form of communication that records elements of required processes and mining practices developed for the operation. They also provide a basis for the effective implementation of the management review stage of the risk management process shown diagrammatically in Figure 2.

RISK MANAGEMENT PROGRAM MONITORING AND REASSESSMENT

The process of monitoring, review and feedback is essential to the effective implementation of a risk management system, particularly in the context of geotechnical risks associated with the development of large open pit slopes. Periodic review is essential to ensure that the geotechnical and slope management plan remains relevant and useful. Since factors that affect likelihood and consequences of unwanted events will change during mine planning and development, it is necessary to reassess the risk management process periodically, especially at each stage or level of mine development.

Elements of an effective risk management program that should be developed and described in the Operation's GMP should include the following:

- Risk identification and risk ratings for all geotechnical risks identified during the feasibility, detailed design and operational stages;
- A risk management plan for high level risks identified in the risk assessments;
- Risk reduction controls for those risks which can be reduced with proper engineered controls;
- For risks managed with a risk reduction plan, a contingency, or trigger action response plan (TARP) for each trigger level associated with the potential for high risk, including:
    - the level at which these measurements become of concern - "trigger level", or "threshold level";
    - communications relating to ground control; how these communications are implemented and where records are filed;
- Assignment of responsibilities for taking corrective action, designing and implementing risk controls and reporting events that will initiate the contingency plan;
- Definition of the role of the geotechnical engineer;
- Filing of incident reports of slope instability, analyses, and records of routine inspections;
- Filing of rehabilitation plans and geotechnical instructions;
- Provision for and content of training programs related to ground control;
- Provisions for regular scheduled reviews, or audits to ensure effectiveness and compliance with all risk management plans in order to adapt to changing mine conditions and processes.

However, even with the development and utilization of best practice in corporate governance and the implementation of a robust risk management system, low probability/high consequence events, like slope instabilities, are still possible in large open pits. Effective slope performance monitoring is the best means of recognizing the onset of instability and awareness of a developing hazardous situation that could eventually become an emergency. An effective emergency response plan (ERP) can prevent an emergency from becoming a disaster. It is also necessary to have recovery and business continuity plans to minimize potential impacts of corrective remediation, commodity supply, regulatory restrictions as well as potential impacts to reputation and community relations.

CONCLUSIONS

In response to the continuing need to improve safety, environmental and operational performance, the increasing utilization of formal and systematic risk assessment and management procedures in the mining industry are positive developments. Nevertheless, low probability/high consequence events such as slope instabilities may continue to occur in small and large open pits. In order to ensure that such events are operationally manageable and do not escalate to the level of an emergency, the assessment and management of risk are becoming integral components of project development from the conceptual design level, to detailed design for construction, to sustaining operations.

The range of existing factual data available and application in the development of interpretive geological and geotechnical models will result in the development of uncertainty in the risk assessment process. The level of geotechnical uncertainty decreases as more data, including performance monitoring records, become available as the project develops. Inherent uncertainty must be recognized and recorded at each stage of the analytical process in terms of the assessment of confidence levels. The level of uncertainty in any design involving the excavation of earth materials should be factored into the design criteria.

Deterministic and risk based approaches are both utilized to assess geotechnical risk for a mining project. Accuracy of these approaches is validated through applied excavation experience. The risk based approach may be used to quantify the levels of risk associated with optional pit design configurations, or development sequence phases, and facilitates the development of slope management plans. The risk based design approach should be explored for purposes of optimizing (balance of safest and steepest) slope designs and maximizing economic return.

The principal goals of an effective geomechanics management program are achieved with an effective performance monitoring system, and where mine operators are well aware of the potential hazards. Field observations, including quantitative measurements obtained from field instrumentation, provide the means by which the geomechanics engineer can evaluate slope performance, and mine operations can execute the work with safety and economy. The process of monitoring, review and feedback is essential to the effective implementation of a risk management system, particularly in the context of geotechnical risks associated with the development of large open pit slopes.

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