DEVELOPMENT OF A DECISION TOOL FOR SELECTION OF PIT SLOPE STABILITY MONITORING INSTRUMENTATION

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Pit slope instability can have significant impacts to mining operations, mine economics and safety. Slope stability monitoring can reduce those impacts by providing time for preparation and potentially remediation of slope displacement. Effective selection of slope stability monitoring systems for open pit slopes has been a challenge for mine operators. Challenges are principally due a lack of a consistent approach that can provide instrumentation recommendations for a specific slope and the wide range of available instrumentation that are currently available, from simple inexpensive methods such as visual inspection to more complex and costly methods such radar monitoring. This paper presents a Slope Stability Monitoring decision tool that has been developed to consistently and efficiently select instrumentation across a range of pit slope characteristics. The Slope Stability Monitoring decision tool uses typical slope stability evaluation criteria to assess the risk of slope instability and provides instrumentation recommendations based on the calculated level of risk.

INTRODUCTION

Effective selection of slope stability monitoring systems for open pits has been a challenge for mine operators. Technological advances in slope stability monitoring systems over the last few decades offer mine operators a variety of monitoring options from which to choose. These monitoring options include, for example, visual inspection (in-person or drone photography), extensometers, inclinometers, survey methods, piezometers, light detection and ranging (LiDAR), and radio detection and ranging (RADAR). There are benefits and limitations to each instrument type. Some instruments are specifically designed for subsurface monitoring and other instruments for surface monitoring. Some instruments offer localized measurements while other instruments allow for scanning of large areas. Remote monitoring and near-real time alarm systems are also available. Investments required for these systems vary greatly (Kane and Beck 2000). All these instrumentation aspects, in addition to the site-specific conditions, create challenges when selecting instrumentation.

The objective of this publication is to present a decision tool for selection of pit slope stability monitoring instrumentation. This decision tool has been developed to consistently and efficiently select instrumentation across a range of pit slope characteristics for open pit mining. The Slope Stability Monitoring (SSM) decision tool evaluates the risk level of a mine site through a series of site-specific inputs. These inputs, provided by the user, are weighted based on their importance with respect to risk. Using these input data, the tool outputs a risk level for the site being evaluated. The site-specific risk level is used to recommend a suite of monitoring instruments

The SSM decision tool is one source of input in recommending a holistic monitoring program. It provides a defensible platform from which an appropriate pit slope monitoring program can be developed. Once a monitoring program is in place, it should be reviewed regularly based on performance and due to the dynamic nature of pit slope characteristics during development.

SSM INSTRUMENTATION OVERVIEW

Slope stability monitoring systems have been developed for open pit mines with the objectives of reducing risk, as well as improving safety and performance (Cawood 2006, Hannon 2007). This section provides an overview of some of the pit slope monitoring systems currently in use.

Slope stability instruments can be categorized based on their ability to measure subsurface or surface movements. The subsurface category includes water level meters, piezometers and inclinometers. The surface category includes extensometers, global navigation satellite systems (GNSS), photogrammetry, LiDAR, total station survey systems and slope stability radar. Three main types of radar monitoring systems are available, InSAR, Real Aperture Radar (RAR) and Synthetic Aperture Radar (SAR). Radar systems are now widely used for pit slope monitoring (Kumar 2015). Figure 1 is a diagram of pit slope monitoring systems considered for this publication.

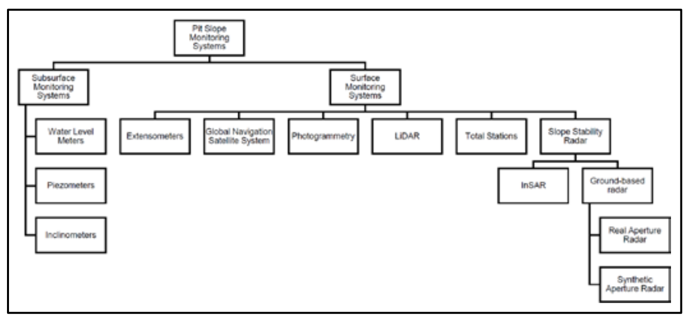

Figure 1. Classification of Pit Slope Monitoring Systems.

SSM DECISION TOOL OVERVIEW

The SSM decision tool was developed to aid in the selection of slope monitoring technologies. The SSM decision tool first evaluates the site-specific risk based on a series of inputs and then outputs a suite of monitoring instruments. This tool can be implemented in a spreadsheet or a similar platform for ease of use by site personnel.

The SSM decision tool should be used for each pit slope design sector or where any significant variation in slope characteristics, including geotechnical or geological characteristics, would require a stand-alone evaluation. Once the instrumentation selection is completed for each design sector using the SSM decision tool, site personnel should consider the instrumentation needs for multiple design sectors. For instance, if the SSM decision tool indicates that SAR is required for one design sector but not necessarily warranted for the other design sectors, the SAR might be able to monitor several sectors and could therefore be more cost effective compared to a combination of different instruments specific to the minimum needs of each design sector.

The SSM decision tool was developed to provide instrumentation recommendations based on a limited number of inputs. Many additional input parameters have been considered during the development phase. The authors observed that adding parameters reduces repeatability without improving the accuracy of the risk evaluation and instrumentation recommendation. Therefore, the number of data input inquiries has been reduced to critical questions to improve repeatability. Similarly, slope failure mechanism is an essential aspect of instrument selection. The SSM decision tool has been developed with the objective of recommending instrumentation capable of detecting different failure modes because slope failure mechanisms are not always fully understood by site personnel or engineers. The failure mode is therefore not an input in the SSM decision tool.

Once the instrumentation selection using the SSM decision tool is completed, site personnel, engineers, and possibly the equipment suppliers, should evaluate the quantity and the most effective placement for the recommended instrumentation.

SSM DECISION TOOL RISK EVALUATION

The SSM decision tool evaluates the risk of slope failure based on several site-specific inputs provided by the users. An individual risk score is assigned to each input. Each individual risk score is then weighted based on its importance with respect to slope stability risk. Table 1 (see APPENDIX) provides a summary of the individual risk score for each input and its associated weight. The weighted individual risk scores are summed to obtain an overall risk score used to characterize the risk level of the pit slope evaluated. The risk level obtained is then used to provide recommendations for slope monitoring instrumentation.

Risk Data

Specific slope stability risks are evaluated through a series of inputs that are classified into five categories:

- Risk Exposure
- Site Assessment
- Design
- Geotechnical
- Hydrogeology

Each input provided by site personnel is given an individual risk score ranging from 0 to 10, with 0 having the lowest risk level and 10 having the highest risk level. Each risk score is weighted to account for the criticality with respect to slope stability as compared to the other inputs. For example, the weight given to the potential damage to critical infrastructure is higher than the weight given to pit mapping because risks associated with critical infrastructure, in the case of a slope failure, is higher than the risk associated with a lack of pit mapping. The weightings for each inquiry have been estimated based on the authors' experience with pit slope engineering and performance. The individual weighted risk scores are summed to obtain an overall score.

Risk Exposure. The exposure category corresponds to the potential human casualties (from potential minor injuries to potential loss of life) and the potential financial losses in case of a slope failure. The risk exposure includes human and financial exposure. The human exposure input is the maximum number of people that can be affected by a potential failure of the slope being evaluated at a given time. The term "people" refers to those who have legal access to the site including mine employees, contractors, subcontracts, visitors. Those people who illegally access the site should also be accounted for to the extent practical. "Affected" means physical or psychological injuries beyond first aid. In general, the maximum number of people that can be affected by a potential slope failure corresponds to people located in the vicinity of the slope, including upgradient and downgradient of the slope, at a given time. The financial exposure input is total potential financial loss as a consequence of failure of the slope evaluated. This includes equipment and structures as well as cost of remediation and lost production revenue.

Site Assessment. The site assessment category corresponds to general observations of the site being evaluated that can affect the risk associated with slope stability. These include previous slope displacements or failures that involve two or more benches in height. Observed displacement or failure can be visual or measured by instrumentation. Occasional displacements observed at the single bench scale height level or less should be omitted. The remediation status of the previous slope displacement or failure is input. Remediation includes buttressing, removal, mechanical slope stabilization, abandonment of the slope and the like. Annual precipitation and rainfall patterns are also considered.

Design. The design category incorporates information regarding the design of the slope being analyzed including slope height, design level, number and placement of coreholes as well as the presence of a lithology and alteration block model. The slope height input is the height of the pit slope evaluated from the toe to the crest of the slope within the time frame being considered for monitoring. Mine operators might want to consider the pit height at the end of the fiscal year or following fiscal year for planning purposes and budget allocation. The design level input refers to the design level of the slope being evaluated as indicated in the most recent slope stability evaluation report. This includes pre-feasibility, feasibility, and detailed design levels.

The number of geotechnical coreholes input corresponds to the number of geotechnical coreholes used for the slope design located within the slope being evaluated (typically a design sector). The "ideal" condition would be at least one geotechnical corehole per design sector, which is typical at the feasibility and design levels. Design sectors are selected based on face aspects and rock mass characteristics.

The lithology and alteration block model inputs inform of the availability of lithology and/or alteration block models and of their use for the pit slope stability evaluation. The purpose of this function is to differentiate between pit slope design that is based on interpretation of rock mass characteristics from limited data, such as a single corehole per design sector, compared to pit slope design that has been completed using a three-dimensional block model of lithology and alteration that has been developed based on data from numerous (including exploration) drill holes. The incorporation of a lithology and alteration block model into the geotechnical model used for pit slope evaluation significantly increases confidence in the resultant pit slope recommendations.

Geotechnical. The geotechnical category provides input on the geotechnical characteristics of the slope being evaluated. The geotechnical engineer on site input specifies the site visit frequency of the geotechnical engineer. The purpose of this input is to differentiate between sites for which the geotechnical engineer is actively involved in the development of the pit and sites for which the geotechnical engineer is rarely consulted following the submission of the design. The relationship with design engineer input provides information regarding the interaction between the mine and the design engineer. Pit slopes are best optimized when designs are adjusted to reflect actual pit conditions as they are revealed during excavation.

The rock mass rating input corresponds to the rock mass rating (RMR) as defined by Bieniawski (1989). In the case of soil like materials, a very poor rock mass rating should be selected. Rock mass strength variability input is used as an indication of the subsurface variability of the rock mass for the slope being evaluated. For example, a low strength variability would be expected for stratiform deposits, because rock mass characteristics, including rock mass strength, is typically fairly uniform with these types of deposits. A moderate rock mass strength variability would be expected in the case of disseminated porphyry deposits, for example. A highly variable rock mass strength would be expected for epithermal deposits due to alteration halos in which high strength silicic altered zones are present along with varying degrees of argillic alteration. There are, of course, other types of ore deposits and exceptions to any of these three cases. The operator should choose based on the intent of this input and not strictly upon the deposit type.

The pit mapping for rock mechanics input refers to the degree of geotechnical pit mapping that is conducted during pit excavation, including fault zones, discontinuities, material strength, alteration and lithology.

Hydrogeology. The hydrogeology category provides input on the hydrogeologic characteristics of the slope being evaluated. The phreatic surface elevation input is the maximum phreatic surface elevation in the vicinity of the slope being evaluated in relation to the pit bottom that will be reached during the time period for which the evaluation is being conducted.

The piezometer readings input provides information about the piezometer reading(s) in relation to the pore pressure thresholds, as defined in the design report, to meet slope stability requirements. If several piezometer readings are available in the vicinity of the slope being evaluated, the most critical readings, as compared to thresholds, should be used. The hydrogeology evaluation input specifies if a local hydrogeology evaluation has been conducted and used in the slope stability analyses. Regional evaluations should not be considered unless there was a local component. Similarly, for example, spreadsheet based hydrogeologic models that are not based on actual aquifer characteristics, such as permeability, should not be included.

Risk Score

A risk level for the slope studied is defined based on the calculated risk score. The risk levels are:

- Level 1: Low
- Level 2: Intermediate
- Level 3: Medium
- Level 4: High
- Level 5: Critical
- Level 6: Safety Critical

Level 1 corresponds to the lowest risk level. Level 6 represents an unacceptable risk level and requires immediate attention from the geotechnical engineer, design engineer and health and safety personnel. In the case of an operating pit, the action at Level 6 could include a stop work order. Level 5 is the highest level for which slope monitoring instrumentation can be useful in mitigating the risk.

The SSM decision tool first calculates a risk level for the slope being evaluated. If the calculated risk score falls within the risk range of a given risk level, then that risk level is output by the tool. Technical constraints imposed a non-linear range, with larger risk score ranges for higher risk levels. The non-linear range is a consequence of higher weighting for inputs considered riskier with respect to slope stability. A dual range has been created to account for the technical constraints and ease of use. The SSM decision tool calculates the risk level based on the non-linear range but a linear range is output and displayed to the user. The relationship between the non-linear and linear ranges is provided in Table 2.

Table 2. Risk Ranges.

	Initial Range (Non-Linear)	Adjusted Range (Linear)
Level 6	Above 5,500	9,000 to 10,000
Level 5	5,000 to 5,500	7,000 to 9,000
Level 4	900 to 5,000	5,000 to 9,000
Level 3	650 to 900	3,000 to 5,000
Level 2	275 to 650	1,000 to 3,000
Level 1	0 to 275	0 to 1,000

INSTRUMENTATION SELECTION

Once the risk level has been defined, the instrumentation selection is performed using the instrumentation selection guideline, provided in Table 3 (see APPENDIX). The instrumentation selection guideline provides a suite of recommended instrumentation for each risk level. The recommended instrumentation for each risk level is selected to efficiently address the slope stability risks. A higher risk level requires additional and/or more advanced instrumentation. Risks associated with Level 6 cannot be mitigated with instrumentation and immediate remediation (along with all safety considerations) should be implemented. As previously mentioned, in the case of operating pits, a stop work order may be appropriate for Level 6.

The SSM decision tool should be used for each design sector or where any significant variation in slope characteristics, including geotechnical or geological characteristics, would require a separate evaluation. Depending on slope characteristics, it is possible that the recommended instrumentation could vary from one sector to another. Upon completion of the instrumentation evaluation for each sector using the SSM decision tool, the user should assess which instrumentation system would be the most cost effective to monitor the different design sectors. For example, if a permanent SAR is recommended for a design sector and a periodic LiDAR is recommended for another design sector, the permanent SAR might be able to cover the other design sector for which LiDAR is recommended. Because a permanent SAR would provide a higher monitoring level than the monitoring level of a periodic LiDAR, it is acceptable to substitute the periodic LiDAR monitoring for a periodic or permanent SAR.

USE OF THE SSM DECISION TOOL

Upon selection of monitoring instrumentation using the SSM tool, site personnel, engineers, and possibly the equipment suppliers, should select a specific type of instrument, including brand and model, and define the installation layout.

The list of instrumentation recommended by the SSM decision tool is by no means exhaustive. Additional instrumentation can be installed to identify potential risks not captured by the recommended instrumentation.

Training of site personnel is critical to the proper use of the SSM decision tool. The authors recommend that one or several on-site employee(s) be designated to be responsible for the use of the SSM decision tool and for the instrumentation selection for each site. Employees responsible for the instrumentation selection should have the authority to access information and data needed for the use of the SSM decision tool.

It is important for mine operators to encourage a direct communication between the employees responsible for the slope monitoring system and the health and safety personnel. The objectives are to assign responsibilities for regular updates of the SSM decision tool and associated instrumentation recommendations and to facilitate transfer of information between site employees and the health and safety personnel. It is critical for the health and safety personnel to receive regular information and feedback from site employees to identify and mitigate potential issues as well as improve consistency between sites regarding instrumentation selection.

CONCLUSIONS

The SSM decision tool presented in this paper provides a simple and effective way of selecting the suite of instrumentation required for a particular pit slope. The SSM tool provides instrumentation recommendations in two stages:

1. Estimate the risk level of the pit slope being evaluated based on a series of inquiries, and
2. Provide instrumentation recommendations for an estimate risk level.

The SSM decision tool should be used for each design sector or where slope characteristics, including geotechnical and geological characteristics, are variable. The SSM decision tool should be updated every three months at a minimum, for active zones or as warranted by changes in slope stability, or when new information is available. The SSM decision tool should be updated annually for inactive zones or as warranted by changes in pit slope stability or when new information is available. Once the SSM tool recommendation is obtained for each design sector, the user should evaluate the most cost-effective instrumentation, considering results for all design sectors.

The SSM decision tool has shown to recommend proper instrumentation for several open pit slopes that have been evaluated by the authors. Additional testing of the decision tool is recommended. The information necessary to develop a similar SSM decision tool is provided herein. Any use by any party of any of the information, opinions, or conclusions is the sole responsibility of said party.

REFERENCES

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APPENDIX

Table 1. Risk Score Logic.

Category	Inputs	Individual Risk Score	Weight
Risk Exposure			
Human	No personnel or non-critical access 1 to 5 more than 5	0 5 10	60
Financial	Less than $100,000: Minor Equipment $100,000 to $500,000: Minor Infrastructure or Major Equipment $500,000 to $1,000,000: Infrastructure, Major Equipment $1,000,000 to $5,000,000: Minor Production Loss, Major Infrastructure or Major Equipment More than $5,000,000: Major Production Loss, Major Infrastructure	0 2.5 5 7.5 10	30
Site Assessment			
Observed Displacements or Failures	Yes No	10 0	50
Observed Displacements or Failures Status	N/A Inactive, Failures or Diplacements Remediated Active, Failures or Diplacements not Remediated	If no observed displacements or failures, 0, otherwise 10 0 If no observed displacements or failures, 0, otherwise 10	350
Annual Precipitation	Less than 500mm 500mm to 1000mm More 1000mm	0 3 10	10
Rainfall Pattern	Moderate / Throughout Year Sustained with High Intensity Events	0 10	30
Design			
Slope Height	0m to 50m 51m to 100m 101m to 150m 151m to 200m More than 200m	0 2.5 5 7.5 10	60
Design Level	Pre-feasibility Feasibility Detailed Design	10 5 0	90
Number Geotechnical Coreholes	0 1 or more	10 0	40
Lithology Block Model	Complete, Up-to-Date Partial, Up-to-Date Complete, Outdated Partial, Outdated Not Existing	0 5 7 10 10	5
Alteration Block Model	Complete, Up-to-Date Partial, Up-to-Date Complete, Outdated Partial, Outdated Not Existing	0 5 7 10 10	5
Geotechnical			
Geotechnical Engineer on Site	Permanent Quarterly or more Frequently As requested or less than Quarterly	1) If pit height less than 50m, then 0 2) If relationship with design engineer is formal or embedded within management of change processes, then 0 3) Otherwise, Permanent = 0 ; Quarterly or more Frequently = 5 ; As requested or less than Quarterly = 10	10
Relationship with Design Engineer	Non Existing Adhoc Formal Embedded within management of change processes	10 7.5 2.5 0	30
Rock Mass Rating	0 to 20, Very Poor 21 to 40, Poor 41 to 60, Fair 61 to 80, Good 81 to 100, Very Good	10 7.5 5 2.5 0	30
Pit Mapping for Rock Mechanics	Permanent Occasionally Very Rarely	0 7 10	5
Rock Mass Strength Variability	Low Moderate High	0 5 10	5
Hydrogeology			
Phreatic Surface Elevation	Below Ultimate Pit Elevation Above Ultimate Pit Elevation	0 10	10
Piezometer Readings	No Piezometers or Readings Below Threshold Below Threshold, but within 5m of Threshold At or Above Threshold	1) If Phreatic surface elevation lower than ultimate pit elevation, 0 2) Otherwise , Below Threshold = 0 ; Below Threshold, but within 5m of Threshold = 2 ; At or Above Threshold = 10; No Piezometers or Readings = 10	50
Hydrogeology Evaluation Conducted	Yes No	0 10	20

APPENDIX (cont'd)

Table 3. Risk Levels and Instrumentation Guideline.

Risk Level		Risk Score	Instrument 1	Instrument 2	Instrument 3	Instrument 4	Instrument 5
Level 6[(1)]	**Safety Critical**	**9,000 - 10,000**	Visual Inspection Evaluation of tension cracks, rockfall, water conditions	Piezometers [(2)] Phreatic elevation above ultimate pit elevation	Extensometers[(3)] Tension crack displacement	Permanent RAR Targeted monitoring of established risk areas	
Level 5	**Critical**	**7,000-9,000**	Visual Inspection Evaluation of tension cracks, rockfall, water conditions	Piezometers [(2)] Phreatic elevation above ultimate pit elevation	Extensometers[(3)] Tension crack displacement	Permanent RAR Targeted monitoring of established risk areas	
Level 4	**High**	**5,000-7,000**	Visual Inspection Evaluation of tension cracks, rockfall, water conditions	Piezometers [(2)] Phreatic elevation above ultimate pit elevation	Extensometers[(3)] Tension crack displacement	Permanent SAR For background monitoring, scans wide areas	Total Station (Optional) Evaluation of displacement using prisms
Level 3	**Moderate**	**3,000-5,000**	Visual Inspection Evaluation of tension cracks, rockfall, water conditions	Piezometers [(2)] Phreatic elevation above ultimate pit elevation	Total Station Evaluation of displacement using prisms	Permanent LiDAR or Periodic SAR For background monitoring, scans wide areas	
Level 2	**Intermediate**	**1,000-3,000**	Visual Inspection Evaluation of tension cracks, rockfall, water conditions	Piezometers [(2)] Phreatic elevation above ultimate pit elevation	Total Station Evaluation of displacement using prisms	Periodic LiDAR or InSAR Pit wall imaging for evaluation of displacement	
Level 1	**Low**	**0 - 1,000**	Visual Inspection Evaluation of tension cracks, rockfall, water conditions	Piezometers [(2)] Phreatic elevation above ultimate pit elevation	Total Station Evaluation of displacement using prisms		

Notes:
(1) Immediate attention required
(2) Piezometers should be installed when phreatic elevation is above the ultimate pit elevation
(3) Extensometers should be installed when tension cracks are visible and safely accessible