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A Geotechnical Risk Assessment Tool for Underground Mine Drives

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ABSTRACT

Rockfalls or significant deterioration of mine openings can have significant safety and financial impacts for mining operations. The failure of drives in underground mines sometimes highlight deficiencies in the mine risk management systems in detecting geotechnical hazards and to prevent events that can have significant impact. Consequences from these failures includes fatalities, injuries, loss of revenue, additional cost, and potentially a loss in Ore Reserves. Where the impacts are severe, it also affects families and communities linked to the operation. The assessment of underground excavations requires consideration of the full range and spectrum of geotechnical hazards, design aspects, ground support, layouts and sequences. Where the assessment of these are insufficient or incorrect, it can result in drive failures. Care must be taken that meeting production targets and personnel pressures do not result in a situation where production take preference over a proper risk-based assessment of the drives to be mined.

The risk management approach is now widely accepted in the mining industry for the control and management of risks in underground mines. Codes of Practices (COP's), Ground Control Management Plans (GCMP), Principal Hazard Management Plans (PHMP's) and technical guidance documents has become the norm for describing the mines main hazards, risk levels and intimating controls for safe passage of vehicles and mine personnel.

However, where there is a disconnect between these documents and what is actually being done at the mine site, the COP's and/or Management Plans become ineffective (or vice versa). This disconnect may occur due to the actual content of these documents, a lack of resources, or a lack of understanding about the implementation.

There is therefore a need for sites to have a documented and implemented risk-based approach for assessing underground mine development. This approach or system needs to identify all hazards and other factors affecting mine development stability early on in the design process, and outline the risk classification and controls required. This paper presents an amalgamation and modification of previous processes for a Geotechnical Risk Management System for Underground Mine Development.

INTRODUCTION

Underground mine excavations are generally developed according to strict mining engineering principles. From time to time these excavations can be exposed to stability issues due to known or unknown factors and circumstances. Following a number of investigations into rockfall accidents that resulted in either serious injuries or fatalities over a span of 28 years for each of the authors, they believe that there are sometimes deficiencies in the technical risk appraisal of underground mine drives. From experience, attempts to manage geotechnical and rock related falls of ground hazards and risks, showed that existing practices had some degree of harm and some hazards were found negligible and sometimes not included in an overall strategy. A mine wide fall of ground incident and / or accident analysis (i.e. baseline geotechnical risk assessment) will assist in defining some of the critical rock mechanics / geotechnical engineering hazards and risks associated with practical mining by mine operators (Hartman, 2004).

The current practice for some Australian mines requires a geotechnical / rock mechanics practitioner to assess a variety of mine tunnels for the purpose of assigning primary and secondary ground control for safe access. Other mines without on-site personnel uses standardised (or empirical) approaches for all development, regardless of potential changing conditions. For on-site personnel the process involves mine planning/design engineers preparing preliminary *Primary Development Designs* (PDD), which is then assessed by the mine Geology, Ventilation and Geotechnical departments for their input and approval. The final approval is provided once the accountable Mine Manager has provided his authorisation. The approved design is then used by the Survey Department to prepare the Survey memo which is used by the development team. At some sites, the PDD is also issued to the *Mine Production Team* or at least the *Mine Production Supervisor* with more details of the assessment available for them to consider. This is an appropriate approach in the assessment and communication of associated hazards/risks for each underground excavation. The challenge is the detail that goes into the design assessments, including the Geotechnical/Rock Mechanics assessment. Is it detailed enough, and what degree of evidence is available that the proposed mine development was assessed to an appropriate requirement?

A RISK OVERVIEW

Risk is an effect of uncertainty on certain objectives (AS/NZS ISO 31000:2009), which can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organizational-wide, project, product and process). Risk is characterised by reference to potential events and consequences, or a combination of these. Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of the event occurrence.

Uncertainty has always been a factor in mining and many decisions traditionally rely on the experience and judgement of operators (Medhurst and Horsley, 2000). Medhurst and Horsley queried whether this uncertainty is acceptable? The authors are of the opinion that uncertainty surrounding risk should never be acceptable even at an early stage of mine tunnel / development assessment. Brown (2012), highlighted Hadjigeorgiou and Harrison (2011) valuable account of uncertainty and the sources of error in rock engineering. In discussing the use of ***rock mass classification schemes*** in the design of underground excavations, they identified two groups of errors.

- The ***first group*** consists of errors *fundamental* to the classification scheme used, including errors of omission, errors of *exaggeration*, and errors of *nomenclature* associated with the requirement to select a particular classification rating value for a geotechnical property.
- The ***second group*** of errors are associated with implementation, and include errors of circumstance, errors of convenience, errors of ignoring variability, and errors of ignoring uncertainty. Thus uncertainty in design and assessment is quite often due to a lack of available data which can result in various misinterpretations.

These items can be fundamental to the implementation of ground control selection. Hartman and Handley (2002) identified that conventional ground control already in use at the Impala Platinum Mine could have prevented all falls of ground if the "*circumstances leading to them*" had been identified beforehand. A fall of ground accident analysis for off-reef tunnels at the mine revealed that nearly all falls of ground were controlled by discontinuities in the rock mass. Hence the Q-Tunnelling Quality Index appeared to be sufficiently flexible to identify the potential fall of ground hazard if it is properly used.

Risk Assessment

Risk assessment is the overall process of risk identification, risk analysis and risk evaluation (AS/NZS 31000:2018).

[Place figure 1 here]

Geotechnical engineers are quite often faced with questions related to the likelihood of an event. Hence in risk management, the word "likelihood" is used to refer to the chance of an unwanted event occurring, whether defined, measured or determined objectively or subjectively, qualitatively or quantitatively, and described using general terms or mathematically (such as a probability or a frequency over a given time period).

The risk level associated with a specific excavation would frequently be ambiguous due to a lack of reliable information for *Geotechnical Engineers*.

Risk Identification

- Risk Identification is the process of identifying and describing risks and involves the identification of risk sources (tangible or intangible, events (incidents or accidents), their causes and their potential consequences (certain or uncertain). It can involve historical data, theoretical analysis, informed and expert opinions, and stakeholder's needs.

Risk Analysis

- The process to comprehend the nature of risk and to determine the level of risk. Risk analysis provides the basis for risk evaluation and decisions about risk treatment.

Risk Evaluation

- Risk evaluation is the process of comparing the results of risk analysis with risk criteria (i.e. production objectives, and external and internal context) to determine whether the risk and/or its magnitude is acceptable or tolerable. Risk evaluation assists in the decision about risk treatment.

CURRENT MINE EXCAVATION (DRIVE) RISK ASSESSMENT PRACTICE

Excavations in underground mines have different shapes and sizes covering various purposes. These excavations may include:

- Declines / Inclines
- Shafts
- Crusher chambers
- Access drives
- Ore drives
- Slot drives
- Egress/Refuge chambers
- Workshops
- Crib rooms

The risk assessment process should consider the controllable and uncontrollable factors which are likely to affect the stability surrounding mine excavations. The process of risk identification is required prior, or at the latest, during the mine design approval process. Many mines have different mine excavation risk assessment processes, which can be a qualitative or quantitative approach, or it can be both or neither. For example, a *Primary Development Design* (PDD) checklist (EHM, 2016) from a typical mine site can have the following questions for the geotechnical engineer to answer as part of the risk assessment process:

- *Are the ground control requirements and locations clearly shown on the plan? (Yes/No)*
- *If mechanical scaling is not to take place (due to adverse ground conditions), has this been clearly marked / stated on the plan? (Yes/No/NA)*
- *Is the excavation unfavourably oriented with respect to structure? (Yes/No/Unsure)*
- *Have the potential rock failure mechanisms been identified? (Yes/No/Unsure)*
- *Is the area to be subjected to high stress or significant changes in stress? (Yes/No/Unsure/NA)*
- *What are the changes expected and what precautions are required?*
- *Is the proposed excavation an unusual size with special support requirements? (Yes/No)*
- *If the design is for rehabilitation, ensure the following are considered:*
  - *What is the current risk rating (from database or your inspection)? (High/Moderate/Low)*
  - *In high-risk rehabilitation a risk assessment is to be undertaken and attached to the design.*
  - *Ensure the root causes of the risk ranking are adequately considered.*
- *Are there any other hazards and how are they to be managed? (Yes/No)*

A review of a typical Ground Control Management Plan (GCMP) have identified that there are sometimes inadequacies in this type of risk assessment approach, especially the consistency of the following:

- How the final answers to the design is obtained in the PDD assessment
- The level of detail that goes into it.
- The experience and skills of the Engineer completing the assessment
- The level of localised site knowledge
- Use of data and assessment tools and guidelines

The authors recognise that these inadequacies can result in deficiencies of a mine design system. The need for a consistent approach which incorporate all of the rock mechanics factors impacting excavation stability is required to include both controllable and uncontrollable factors.

MINE EXCAVATION (DRIVE) RISK IDENTIFICATION FACTORS

In 1995 a tunnel risk rating system (Hartman, 1995) was developed which identified some of the factors that impacted on mine drive stability. The tool was mainly used to assist in prioritising the rehabilitation of mine drives. Over time the hazard identification process was refined, geotechnical parameters and conditions were identified that could cause or have the potential to cause rockfalls or excavation instability.

Potvin and Nedin (2003) recognised that ground conditions can have a significant influence on excavation stability. The proposed size, location, shape and orientation of development excavations must take appropriate account of ground conditions and their potential variations with time. For example, the location of main access development too close to future stoping areas can have a significant adverse influence on access stability. The long-term use of main access development can be seriously compromised by inappropriate location. This could occur where excavations are too close to other excavations, stopes, pillars or geological structures.

Hence the identified hazards or factors having a significant influence on excavation stability were separated into *controllable* and *uncontrollable* factors.

Controllable Factors

Controllable factors are described as factors that will influence the mine excavation during and after development and where practitioners /engineers have some control. During the design stage, excavations orientation (e.g. approach to known geological structures) and geometry (shape and size) can be altered. We can further change the position or distance, to and from other excavations.

All these factors with quality geological information at hand are controllable in the sense that poor mine design can be prevented during the planning stage. Drilling and blasting featured heavily during the preparation of the list is an important factor that affects the stability of an excavation. Although the Geotechnical Engineer do not have control over the execution quality of drilling and blasting, he/she must have an input to key considerations for excavation perimeter control. The controllable factors within the ***Mine Drive Risk Index (MDRI)*** risk assessment tool are listed below:

- Excavation type (e.g. Vertical, Horizontal or Incline)
- Geometry of excavation (i.e. width:height ratio)
- Excavation shape (e.g. arched profile – rounded corners, sharp edges or square shape)
- Excavation orientation (i.e. Parallel to maximum principal stress, perpendicular to maximum principal stress)
- Distance from other excavations (i.e. 0m -12m, 12m – 18m or >18m) – excavation stress interaction
- Drilling and Blasting (i.e. drilling accuracy and explosive charge has a significant impact on excavation stability e.g. perimeter control in friable ground, stand-off from geological structure contacts and/or destressing requirements)
- Significant known geological structure (e.g. large faults / zones) intersections, or approach to structure
- Distance from known seismically active geological structures or intrusive dykes (e.g. faults and/or high strength dyke material which may exhibit contrasting deformation)
- Personnel exposure (i.e. None, Low (1-2 persons), Moderate (3-5 persons) or High (>5 persons)

Uncontrollable Factors

The uncontrollable factors are described as factors that will influence the mine excavation during and after development and of which we as practitioners have no control over. During the design stage geotechnical engineers will gather the appropriate geological and geotechnical information which will be analysed during the next stage of the risk assessment process. Hadjigeorgiou and Karampinos (2017) critically assessed the limitations of available empirical tools with reference to squeezing ground. A distinction is made between conditions where the rock mass deforms and fails in a uniform way, and in deep hard rock mines where squeezing is often controlled by structures, anisotropic rock mass conditions, and high stress. This results in non-uniform deformation and buckling failure mechanisms. Potvin and Hadjigeorgiou (2008) reported that high deformations in deep and high stress mines are generally related to the presence of prominent structural features such as a dominant fracture set, intense foliation, shear zones and high stress. These conditions result in a buckling failure mechanism.

The factors involved in the evaluation of squeezing or high deformation relates to stress or induced stress, rockmass strength, foliation, bedding, schistosity, cleavage and their relevant spacing. Ground water presence is an element that is often omitted from assessments due to mines being relatively dry due to dewatering efforts. Some mines though, having reasonable dewatering in place, have uncontrollable seepage, which changes local peripheral stress.

The uncontrollable and in-situ geological and geotechnical factors which can affect the stability of excavations during and after development within a low-stress and high stress (i.e. squeezing, strainburst or rockburst potential) environment are listed below:

- Rock Quality Designation (RQD) – (Deere, 1964).
- Geological Structure (Joint Number - Jn) – (Barton, Lien and Lunde, 1974).
- Rock Mass Strength (MPa) – (Palmström and Singh, 2001).
- Stress Change (i.e. Numerical modelling should be conducted to understand the stress environment and stress change – ensure to utilise rockmass deformation modulus E_m) – (Hoek et al, 2002).
- Ground Water (e.g. Damp, Wet, Dripping or Flowing)
- Seismicity or violent energy release (e.g. Low-level continuous small events, localised strain bursting or rockbursts). Seismicity, to some degree, is influenced by the decisions made around sequencing and pillars. These decisions can make the seismic occurrences either worse or better.

MINE EXCAVATION (DRIVE) RISK ASSESSMENT RATING SYSTEM

The authors are proposing a rating system to provide a consistent risk assessment approach analysing the risk factors in a quantitative manner. This will allow the geotechnical engineer to:

- Quantify the possible outcomes for the proposed mine excavation and assess the probability of achieving specific objectives
- Provide a quantitative approach to making decisions when there is uncertainty of inputs.

The risk assessment system has the following components:

A. Controllable Factors – Mine Drive Risk Index

   [Place Table 1 here]

B. Uncontrollable Factors – Mine Drive Risk Index (Low Stress Environment)

   [Place Table 2 here]

C. Stress Environment) or Uncontrollable Factors – Mine Drive Risk Index (High Stress Environment - Rockburst Potential).

   [Place Table 3 here]

D. Uncontrollable Factors – Mine Drive Risk Index (Squeezing or Creep Environment - High degree of deformation)

   [Place Table 4 here]

Mine drive risk factors weighting

All the identified factors were grouped and subjected to a risk matrix process with the outcome of that process resulted in factors weighted for a quantification process. The matrix process was utilised to make allowance or adjustments in order to emphasize the importance or contribution of the risk factors to excavation instability.

Mine Drive Risk Index (MDRI) – Analysis

Table 5 shows the *Controllable and Uncontrollable Risk Factors* and their particular weightings used in the Mine Drive Risk Index (MDRI) system. The engineer conducting the excavation analysis must use their experience of the mine's ground conditions to anticipate likely future outcomes. The risk analysis process involves developing an understanding of the risk. Risk analysis provides an input to risk evaluation and to decisions on whether risks need to be treated, and on the most appropriate risk treatment strategies and methods

Ratings are assigned for each particular set of circumstance for the Controllable and Uncontrollable factors. The rating number is then adjusted with a weighting according to the importance on the outcome for each of the factors. It is important that weightings are tested on site to make sure their outcome are reflecting the underground reality of the mine. The result for each of the factors is totalled for each specific scenario as outlined in the risk assessment rating system.

[Place Table 5 here]

The proposed risk analysis process requires choices to be made with options for different types and levels of risk. The analysis involves consideration of both the controllable and uncontrollable factors. The consequences and likelihood of factors are evaluated to determine the level of risk. An event can have multiple consequences and can affect multiple objectives. The process also consider the interdependence of different hazards and their sources. Existing controls and their effectiveness are taken into account. The outcome of the risk assessment process also reflect the type of risk and the purpose for which the risk analysis output is to be used.

Mine Drive Risk Index (MDRI) Levels and Acceptance Criteria

The risk assessment and analysis is used to determine the mine drive risk level. Four mine drive risk levels were developed for the three likely conditions:

- Low Stress Environment (i.e. No Seismicity) – see Table 6
- High Stress Environment (i.e. Rockburst Potential) – see Table 7
- High Stress (i.e. Squeezing Potential) – see Table 8

[Place Table 6 here]

[Place Table 7 here]

[Place Table 8 here]

The four risk levels are low, medium, high or extreme. Based on these risk levels, actions and/or controls may be implemented to adhere to an acceptance criteria. Hoek (1991) indicated that there are no simple universal rules for rock engineering design acceptability, nor are there standard factors of safety which can be used to guarantee that a rock structure will be safe and that it will perform adequately. He particularly emphasized that each design is unique and the acceptability of the structure has to be considered in terms of the particular set of circumstances, rock types, design loads and end uses for which it is intended.

The responsibility of the geotechnical engineer would be to find a safe and economical outcome which is compatible with all the constraints which apply to the project. Such an outcome should be based upon sound and consistent engineering process guided by practical and theoretical studies such as stability or deformation analyses, if and when these analyses are applicable. Hence, a combination of changes to the controllable factors could be considered for the residual risk acceptance criteria (Table 9).

[Place Table 9 here]

These actions could be due to likely changes to some, or all of the controllable factors. It can introduce controls to change the residual risk level for the mine drive risk analysis.

PRACTICAL IMPLEMENTATION OF THE MINE DRIVE GEOTECHNICAL RISK ASSESSMENT TOOL

- Example 1 – Moderate seismic risk area

[Place figure 3 here]

[Place figure 4 here]

The rating system has produced a "*High Ris*k" outcome for this area due to the presence of localised Geological structures, the seismicity experienced in this area, a rockmass that is relatively stiff, and high stress conditions. This rating is in line with what is experienced underground at the site where this rating was completed. The area experience some of the largest seismic events on site, with a mMax of 1.6ML.

[Place figure 5 here]

- Example 2 – Low to Moderate seismic risk area

[Place figure 6 here]

[Place figure 7 here]

The rating system has produced a '*Medium Risk*" outcome for this area. The risk level correlates well with the conditions and seismic risk for this area.

Ground Control Selection

The completion of the Geotechnical section of the design approval plan when incorporated with a risk rating system like the MDRI allows the engineer to evaluate the risk associated with the drive, considering its particular circumstances and purpose. A greater understanding of the geotechnical risk environment is achieved and ensures a consistent approach is followed. The ***MDRI Risk Level*** allows early changes in the excavation or drive design. The ground control selection process / flowchart for approval plans shows that all the controllable and uncontrollable factors are considered (Figure 8).

[Place figure 8 here]

As a reminder there are a number of factors to account for when determining static and dynamically capable support and reinforcement. A relative stiffer and stronger rock mass material caused the rock bolt to fail within a lower shear displacement compared to a relatively softer and weaker material (Mahoney et al, 2005) . The more favourable approach is to take into account the energy capacity at which the rock mass will hold or exhibit. When energy considerations are based on seismic activity, the support and reinforcement should at least be able to withstand the potential energy that the rock mass could exert, for a specified location, deformation, velocity and displacement (Hartman, 2017). It would be necessary to allow for loading conditions when assigning peak and residual load capacities for various rock reinforcement elements as Hartman and Rademan (2000) have shown reduced capacities for stiff elements subject to bending moment.

Table 10 below shows examples of controls for various risk levels.

[Place Table 10 here]

CONCLUSIONS

- The Mine Drive Geotechnical Risk Assessment system allows for a consistent approach to consider all of the important factors that influence drive stability. The same methodology is used by all of the Engineers, making sure experience levels or lack of awareness on requirement is not a factor.
- The system also ensures that the decision for a certain type of ground control for an area can be quantified and proof exists that a process was followed where all the required parameters for such an assessment were considered. .
- The system elevates the Geotechnical Engineer's awareness of potential destabilising factors in a specific area.
- Obtaining a risk rating is useful in illustrating to managers and superintendents what the risk is during development, and why certain ground control is required.

ACKNOWLEDGEMENTS

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FIGURES

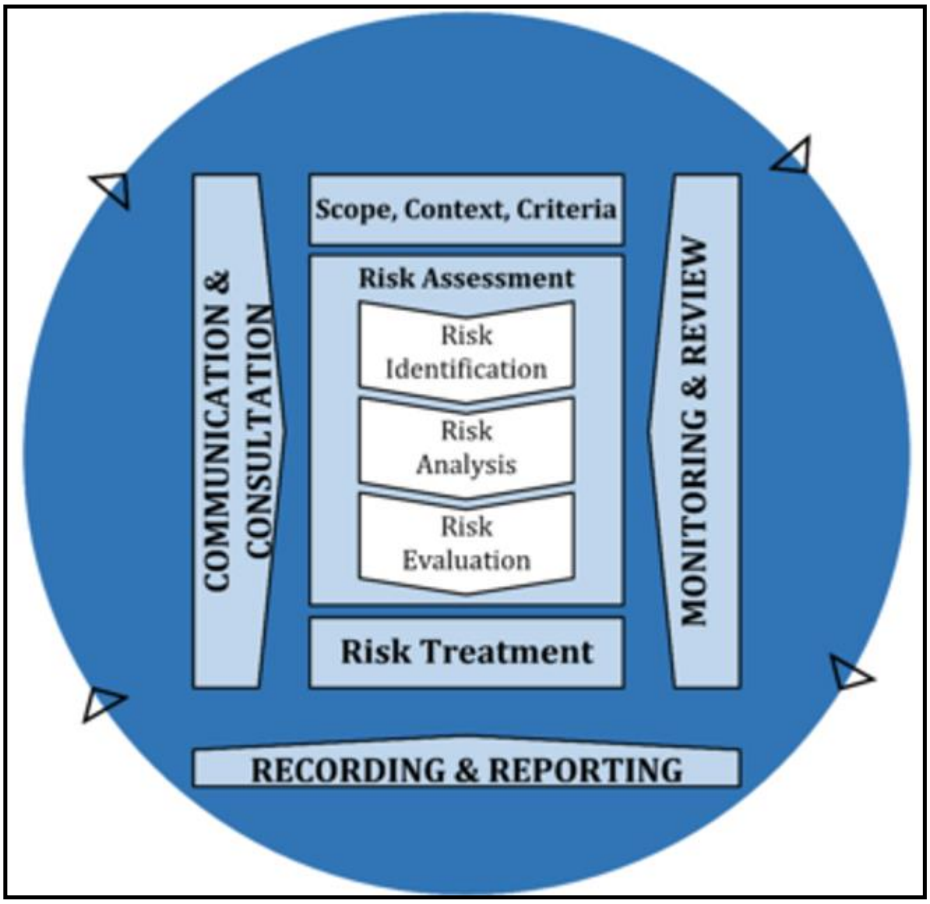

FIG 1 – Risk Assessment process (AS/NZS 31000:2018).

MINE DRIVE RISK ASSESSMENT SYSTEM AND ANALYSIS			Date:	8/09/2018		
High Seismic Risk Area.			Drive Name:	1400 Western Ore Drives OD's 3-9		
		Criteria for Tunnel Index		Rating Number	Weighting	Outcome
A	Controllable Factors	1. Development Type		2	1	2
		2. Geometry of Excavation (Width : Height ratio)		1	4	4
		3. Excavation Shape		1	2	2
		4. Development Orientation		2	2	4
		5. Distance from other excavations		3	3	9
		6. Drilling and Blasting Practice		3	3	9
		7. Significant Geological Structure (Large Faults) intersection		2	5	10
		8. Distance from known seismically active Faults		2	6	12
		9. Mine Personnel Exposure		1	7	7
	AND			Total		59
		Criteria for Tunnel Index - Low Stress Environment		Rating Number	Weighting	Outcome
B	Uncontrollable Factors	1. Rock Quality Designation (RQD)			3	0
		2. Geological Structure			4	0
		3. Rock Material Strength (MPa)			2	0
		4. Stress Change			2	0
		5. Ground Water (Groundwater weighting adjustment for corrositivity - weighting of 4 change to 5)			5	0
	OR			Total		0
		Criteria for Tunnel Index - High Stress Environment		Rating Number	Weighting	Outcome
C	Uncontrollable Factors	1. Rock Quality Designation (RQD)		4	3	12
		2. Geological Structure		2	3	6
		3. Rock Material Strength (MPa)		4	2	8
		5. Ground Water (Groundwater weighting adjustment for corrositivity - weighting of 1 change to 2)		2	2	4
		5. Stress Change		2	2	4
		6. Seismic Risk		2	5	10
	OR			Total		44
		Criteria for Tunnel Index - High Stress Environment (Squeezing Potential)		Rating Number	Weighting	Outcome
D	Uncontrollable Factors	1. Rock Quality Designation (RQD)			2	0
		2. Geological Structure			2	0
		3. Rock Material Strength (MPa)			4	0
		4. Ground Water (Groundwater weighting adjustment for corrositivity - weighting of 1 change to 2)			2	0
		5. Stress Change			2	0
		6. Seismic Risk			5	0
				Total		0

FIG 2 - Example 1 – Moderate seismic risk area.

Mine Drive Risk Index - Level	
Drive Name:	1400 Western Ore Drives OD's 3-9
Date:	8/09/2018
Category A	59
Category B	0
Category C	44
Category D	0
Risk Index	103
Risk Category	High

FIG 3 - Example 1 – Drive Risk Index Levels.

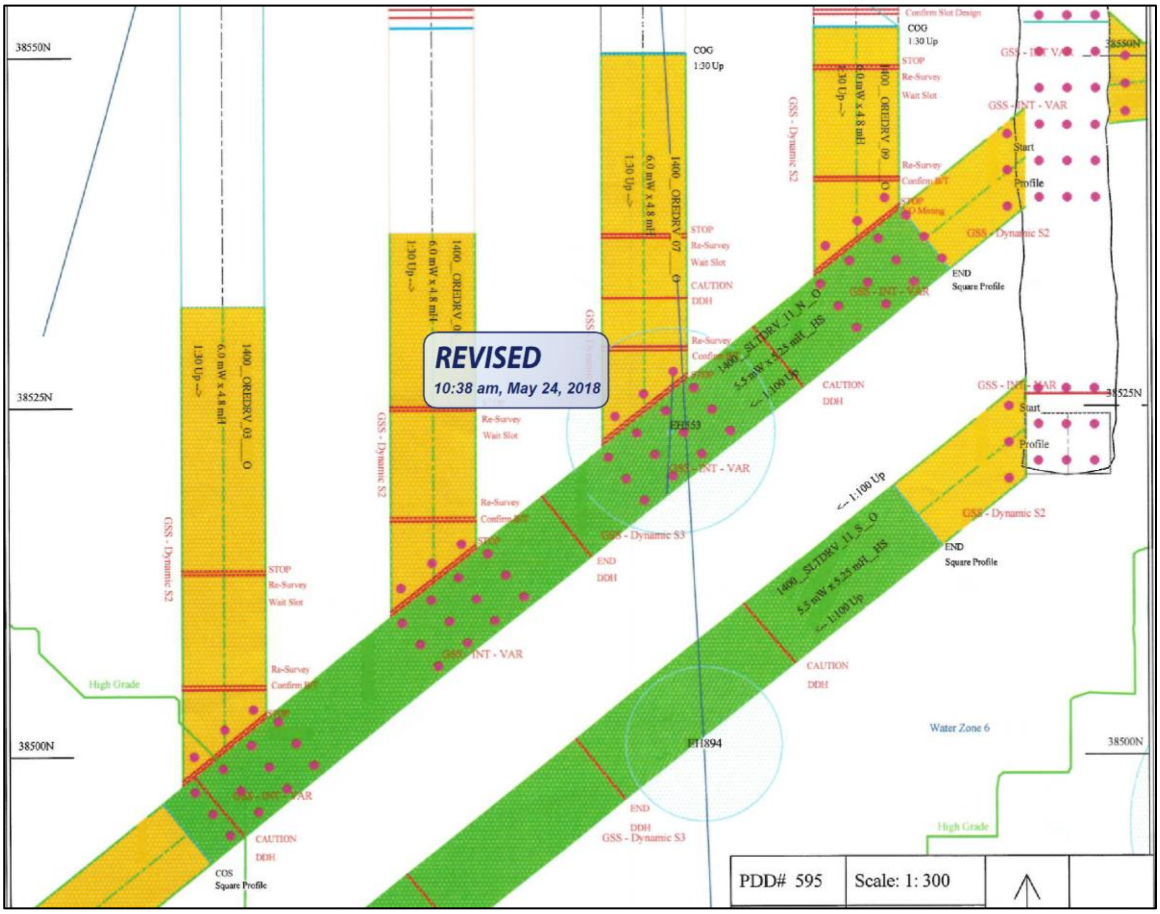

FIG 4 - Example 1 – 1400 Western Ore Drives OD's 3-9.

MINE DRIVE RISK ASSESSMENT SYSTEM AND ANALYSIS		Date:	8/09/2018		
Low - Moderate Seismic Risk Area.		Drive Name:	1375 OD's 4-24 Turnouts		
		Criteria for Tunnel Index	Rating Number	Weighting	Outcome
A	Controllable Factors	1. Development Type	2	1	2
		2. Geometry of Excavation (Width : Height ratio)	1	4	4
		3. Excavation Shape	1	2	2
		4. Development Orientation	2	2	4
		5. Distance from other excavations	2	3	6
		6. Drilling and Blasting Practice	1	3	3
		7. Significant Geological Structure (Large Faults) intersection	0	5	0
		8. Distance from known seismically active Faults	0	6	0
		9. Mine Personnel Exposure	1	7	7
			Total		*28*
	AND				
		Criteria for Tunnel Index - Low Stress Environment	Rating Number	Weighting	Outcome
B	Uncontrollable Factors	1. Rock Quality Designation (RQD)		3	0
		2. Geological Structure		4	0
		3. Rock Material Strength (MPa)		2	0
		4. Stress Change		2	0
		5. Ground Water (Groundwater weighting adjustment for corrositivity - weighting of 4 change to 5)		5	0
			Total		*0*
	OR				
		Criteria for Tunnel Index - High Stress Environment	Rating Number	Weighting	Outcome
C	Uncontrollable Factors	1. Rock Quality Designation (RQD)	2	3	6
		2. Geological Structure	1	3	3
		3. Rock Material Strength (MPa)	4	2	8
		5. Ground Water (Groundwater weighting adjustment for corrositivity - weighting of 1 change to 2)	1	2	2
		5. Stress Change	1	2	2
		6. Seismic Risk	2	5	10
			Total		*31*
	OR				
		Criteria for Tunnel Index - High Stress Environment (Squeezing Potential)	Rating Number	Weighting	Outcome
D	Uncontrollable Factors	1. Rock Quality Designation (RQD)		2	0
		2. Geological Structure		2	0
		3. Rock Material Strength (MPa)		4	0
		4. Ground Water (Groundwater weighting adjustment for corrositivity - weighting of 1 change to 2)		2	0
		5. Stress Change		2	0
		6. Seismic Risk		5	0
			Total		*0*

FIG 5 - Example 2 – Low to Moderate seismic risk area.

Mine Drive Risk Index - Level	
Drive Name:	1400 Western Ore Drives OD's 3-9
Date:	8/09/2018
Category A	28
Category B	0
Category C	31
Category D	0
Risk Index	59
Risk Category	Medium

FIG 6 - Example 2 – Mine Drive Risk Index - Levels.

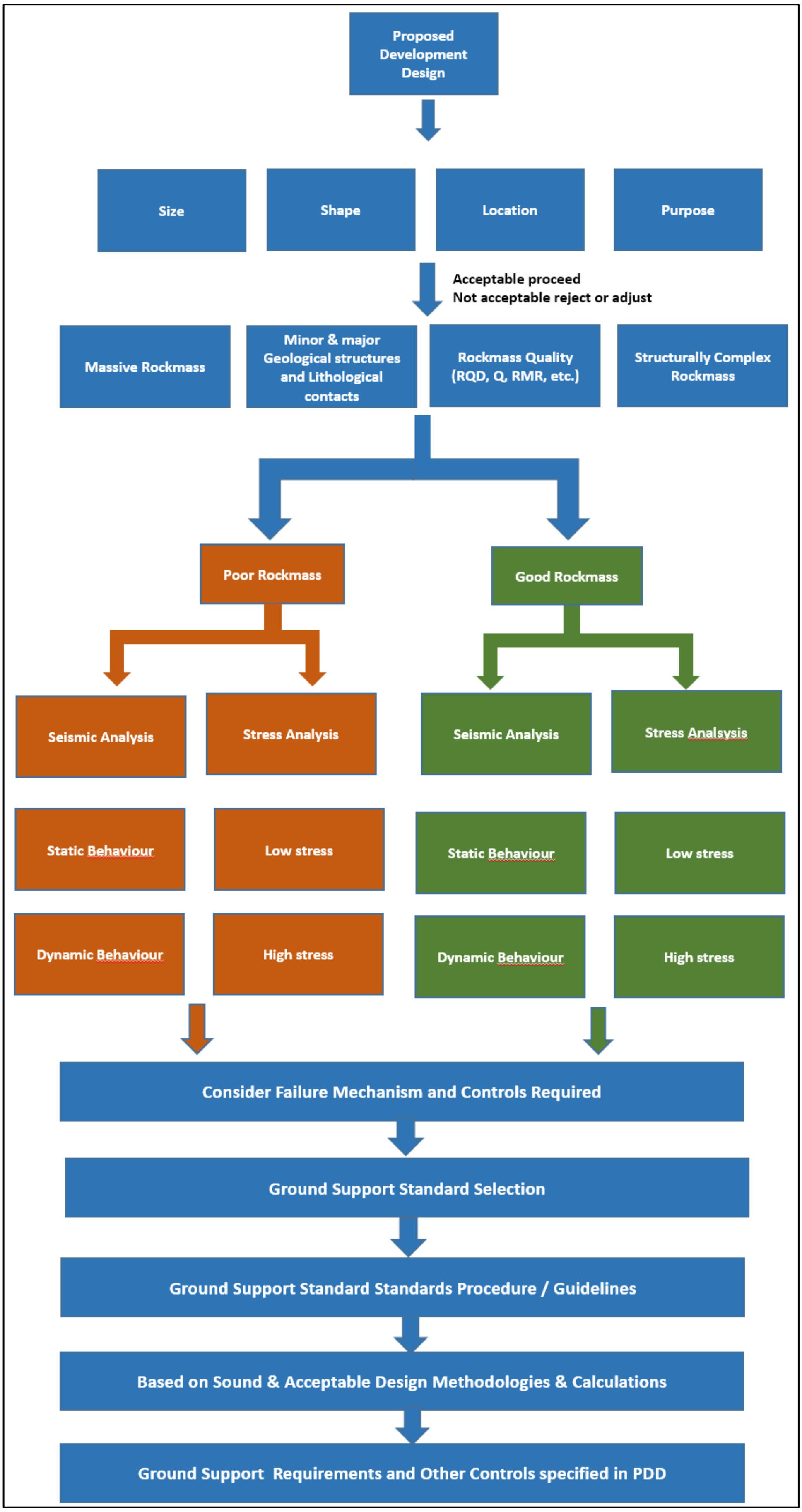

FIG 7 – PDD Design and Ground Support Selection Process.

TABLES

TABLE 1

Risk Assessment for Controllable Factors (Mine Drive Risk Index - MDRI).

	Criteria for Mine Drive Risk Index (MDRI)	Rating Number
Controllable Factors	**1. Development Type**	
	A. Vertical	1
	B. Horizontal	2
	C. Incline	3
	2. Geometry of Excavation (Width : Height ratio)	
	A. 1:1	1
	B. 1:2 or 2:1	2
	C. 1:3 or 3:1	3
	3. Excavation Shape	
	A. Horseshoe (Modified)	1
	B. Backs arched (Rounded corners)	2
	C. Sharp Edges (Square Shape)	3
	4. Development Orientation	
	A. Parallel to Maximum Principal Stress	1
	B. Perpendicular to Maximum Principal Stress	2
	5. Distance from other excavations	
	A. >18m	1
	B. 12m - 18m	2
	C. 0m - 12m	3
	6. Drilling and Blasting Practices	
	A. Normal Drilling Standard (Normal Ground Conditions) or Planning Stage	0
	B. Modified Drilling Standard - High Stress (e.g. Destressing)	1
	C. Modified Drilling Standard - Poor Ground (e.g. Fault zone, blocky ground etc)	2
	D. Normal Drilling Standard (High Stress Conditions / Poor Ground)	3
	7. Significant known Geological Structure (Large Faults or foliation) intersection / approach	
	A. None	0
	B. Normal	1
	C. Oblique	2
	D. Parallel	3
	8. Distance from known seismically active Faults	
	A. None	0
	B. > 50m	1
	C. 25m - 50m	2
	D. 5m - 25m	3

	E. 0m - 5m	**4**
	9. Mine Personnel Exposure	
	A. None	**0**
	B. 1-2 Workers	**1**
	C. 2-5 Workers	**2**
	D. >5 Workers	**3**

TABLE 2

Risk Assessment for Un-Controllable Factors (Mine Drive Risk Index - MDRI) – Low Stress Environment.

	Criteria for Mine Drive Risk Index - Low Stress Environment	Rating Number
Uncontrollable Factors	**1. Rock Quality Designation (RQD)**	
	A. 90-100	1
	B. 75-90	2
	C. 50-75	3
	D. 25 - 50	4
	E. <25	5
	2. Geology	
	A. Simple geological structure (Jn Number 0.5 - 3)	1
	B. Minor Variations (Jn Number: 4 - 9)	2
	C. Complex Minor (Severe Jointing Jn Number: 12-20)	3
	3. Rock Mass Strength (MPa)	
	A. >154	1
	B. 100 - 154	2
	C. 50 – 100	3
	D. 10 – 50	4
	E. < 10	5
	4. Stress Change	
	A. Compressive Zone (Low Stress)	1
	B. Compressive Zone / Stress Abutment (Transition Zone)	2
	C. Tensile Zone	3
	5. Ground Water	
	A. Completely Dry	1
	B. Damp	2
	C. Wet	3
	D. Dripping	4
	E. Flowing	5

TABLE 3

Risk Assessment for Un-Controllable Factors (Mine Drive Risk Index - MDRI) – High Stress Environment (Rockburst Potential).

	Criteria for Mine Drive Risk Index - High Stress Environment (Rockburst Potential)	Rating Number
Uncontrollable Factors	**1. Rock Quality Designation (RQD)**	
	A. <25	1
	B. 25 - 50	2
	C. 50-75	3
	D. 75-90	4
	E. 90-100	5
	2. Structural Geology	
	A. Simple geological structure (Jn Number 0.5 - 3)	1
	B. Minor Variations (Jn Number: 4 - 9)	2
	C. Simple geological structure (Jn Number)	3
	3. Rock Mass Strength (MPa)	
	A. < 10	1
	B. 10 – 50	2
	C. 50 – 100	3
	D. 100 - 154	4
	E. >154	5
	4. Ground Water	
	A. Completely Dry	1
	B. Damp	2
	C. Wet	3
	D. Dripping	4
	E. Flowing	5
	5. Positive Stress Change	
	A. Low (0 - 25%)	1
	B. Medium (25 - 50%)	2
	C. High (50 - 75%)	3
	D. Severe (> 75%)	4
	6. Seismic Risk	
	A. None	0
	B. Low (Popping)	1
	C. Medium (Minor Strain Bursting)	2
	D. High Strain Bursting	3
	E. Severe Rock Burst (Incl Shakedown)	4

TABLE 4

Risk Assessment for Un-Controllable Factors (Mine Drive Risk Index) – High Stress Environment (Squeezing / High Deformation Potential).

	Criteria for Mine Drive Risk Index - High Stress Environment (Squeezing Potential)	Rating Number
Uncontrollable Factors	**1. Rock Quality Designation (RQD)**	
	A. 90-100	1
	B. 75-90	2
	C. 50-75	3
	D. 25 - 50	4
	E. <25	5
	2. Structural Geology	
	A. Simple geological structure (Jn Number 0.5 - 3)	1
	B. Minor Variations (Jn Number: 4 - 9)	2
	C. Complex Minor (Severe Jointing Jn Number: 12-20)	3
	3. Rock Material Strength (MPa)	
	A. >154	1
	B. 100 - 154	2
	C. 50 – 100	3
	D. 10 – 50	4
	E. < 10	5
	4. Ground Water	
	A. Completely Dry	1
	B. Damp	2
	C. Wet	3
	D. Dripping	4
	E. Flowing	5
	5. Positive Stress Change	
	A. Low (0 - 25%)	1
	B. Medium (25 - 50%)	2
	C. High (50 - 75%)	3
	D. Severe (> 75%)	4
	6. Seismic Risk	
	A. None	0
	B. Rock Burst (Far Field - Deformation / Shakedown)	1
	c. Rock Burst (Near Field Deformation / Shakedown)	2

TABLE 5

Risk Analysis Controllable Factors and Un-Controllable Factors (Mine Drive Risk Index - MDRI).

		Criteria for Mine Drive Risk Index	Rating Number	Weighting	Outcome
A	Controllable Factors	1. Development Type	3	1	3
		2. Geometry of Excavation (Width : Height ratio)	3	4	12
		3. Excavation Shape	2	2	4
		4. Development Orientation	2	3	6
		5. Distance from other excavations	3	3	9
		6. Drilling and Blasting Practices	3	2	6
		7. Significant Geological Structure (Large Faults) intersection	3	5	15
		8. Distance from known seismically active Faults	4	6	24
		9. Mine Personnel Exposure	3	7	21
AND			***Total***		***100***
		Criteria for Mine Drive Risk Index - Low Stress Environment	**Rating Number**	**Weighting**	**Outcome**
B	Uncontrollable Factors	1. Rock Quality Designation (RQD)	5	3	15
		2. Geological Structure	3	4	12
		3. Rock Material Strength (MPa)	5	2	10
		4. Stress Change	3	2	6
		5. Ground Water	5	5	25
OR			***Total***		***68***
		Criteria for Mine Drive Risk Index - High Stress Environment	**Rating Number**	**Weighting**	**Outcome**
C	Uncontrollable Factors	1. Rock Quality Designation (RQD)	5	3	15
		2. Geological Structure	3	3	9
		3. Rock Material Strength (MPa)	5	2	10
		4. Ground Water	5	2	10
		5. Stress Change	4	2	8
		6. Seismic Risk	4	5	20

OR			Total		72
		Criteria for Mine Drive Risk Index - High Stress Environment (Squeezing Potential)	**Rating Number**	**Weighting**	**Outcome**
D	**Uncontrollable Factors**	1. Rock Quality Designation (RQD)	5	2	10
		2. Geological Structure	3	2	6
		3. Rock Material Strength (MPa)	5	4	20
		4. Ground Water	5	2	10
		5. Stress Change	4	2	8
		6. Seismic Risk	2	5	10
			Total		***64***

TABLE 6

Low Stress Environment (i.e. No Seismicity) – Mine Drive Risk Index Levels.

A+B	Risk Level	Low Stress Environment	
	1	Low	<42
	2	Medium	42 - 84
	3	High	85 - 126
	4	Extreme	>126

TABLE 7

High Stress Environment (i.e. Rockburst Potential) – Mine Drive Risk Index Levels.

A+C	Risk Level	High Stress Environment	
	1	Low	<43
	2	Medium	43 - 86
	3	High	87 - 129
	4	Extreme	>129

TABLE 8

High Stress (i.e. Squeezing Potential) – Mine Drive Risk Index Levels.

A+D	Risk Level	High Stress Environment (Squeezing Potential)	
	1	**Low**	<41
	2	**Medium**	41 - 82
	3	**High**	83 - 123
	4	**Extreme**	>123

TABLE 9

Risk Index Level Acceptance Criteria and Proposed Actions.

Risk Index Level	Criteria for acceptance of Risk and Risk Review	Control Execution Ownership	Action
Extreme	Risk is not desirable. Requires a control rating of Excellent. Control rating of Inadequate is unacceptable. Immediate management attention required to reduce exposure. The risk needs to be evaluated in terms of risk reduction	Technical Services Manager Geotechnical Superintendent	Review design for potential improvements. Review future mining sequence to reduce impact on drive. Review re-entry requirements and seismic controls Highest level of Dynamic ground support for primary support. Horseshoe Development profile. Install secondary support upgrades where required.
High	Risk may be Tolerable or not desirable. Requires a control rating of Excellent (or Adequate but with justification). Control rating of Inadequate is unacceptable.	Geotechnical Superintendent	Install dynamic ground support and horseshoe profile. Install secondary support upgrades where required. Execute agreed and approved mining sequences. Apply Seismic re-entries and other controls where applicable.
Medium	Risk is Acceptable. Requires a control rating of Adequate. Control rating of Inadequate is unacceptable.	Geotechnical Superintendent	Install dynamic ground support ground support. Execute agreed and approved mining sequences. Apply Seismic re-entries and other controls where applicable.
Low	Risk is Acceptable. Requires a control rating of Adequate. Control rating of Inadequate is unacceptable and will require a Treatment	Geotechnical Engineer	Install dynamic support only where on abutments or within step-out zones. Execute agreed and approved mining sequences.

TABLE 10

Site example of controls for various risk levels.

Risk Level	Typical Ground Support	Other controls
Low	Static rockbolts, Weld Mesh	Arched development profile.
Medium	Dynamic rockbolts, Fibrecrete, Weld mesh.	Arched development profile. Perimeter blasting. Seismic re-entry analysis.
High	Dynamic rockbolts, Fibrecrete, Weld mesh, Twin-strand cable bolting at significant fault intersections.	Horseshoe development profile. Perimeter blasting. Seismic re-entry analysis.
Extreme	Dynamic rockbolts, Fibrecrete, Weld mesh, Zero-gauge type strapping, Twin-strand cablebolts.	Horseshoe development profile Perimeter blasting, Sequence optimisation. Seismic re-entry analysis.