Mining Geomechanical Risk 2019 – J Wesseloo (ed.)
© 2019 Australian Centre for Geomechanics, Perth, ISBN 978-0-9876389-1-5
doi:10.36487/ACG_rep/1905_15_Andrijasevich

Construction of a damage risk model for footwall drifts

J Andrijasevich *The University of Western Australia, Australia*

H Basarir *The University of Western Australia, Australia*

J Wesseloo *Australian Centre for Geomechanics, The University of Western Australia, Australia*

Abstract

Current design of underground mine openings involves a great deal of uncertainty as the geotechnical domains in which mines operate are non-homogenous and highly variable in nature. Current industry practice largely follows a deterministic, Factor of Safety based approach. However, final decisions in mining operations are based on both risk and financial cost, rather than probability distributions or Factor of Safety.

The overall aim of the paper is to create a damage risk model for footwall drifts in a mine using the sublevel caving production method. Both numerical and probabilistic outcomes were used to evaluate and assess risk with the aid of a risk matrix. A number of parameters including rock properties, mining-induced stresses and the location of a drift relative to the weakness zone were considered. A special emphasis was placed on the economic consequences of the assessed risk and failure potential, described in terms of drift convergence. Considered economic consequences include rehabilitation, time duration, production loss exposure and delay flexibility, with particular focus applied to shareholder value and public reputation (PR). The associated costs were then compared to find the optimum location for the drift.

Keywords: *risk-based design, probabilistic design, uncertainty, risk model*

1 Introduction

In a competitive global mining environment, designs need to incorporate not only functionality (serviceability), but also expected development and operational costs. Infrastructure serviceability and costings contain a degree of uncertainty and hence carry a level of risk. The profit-generating ability of mining operations can be adversely impacted by uncertainty and the economic consequences of failure, particularly when large scale failures are encountered. A common problem for deep caving operations is the deformation of footwall access drifts due to the effects of mining-induced stresses and geological boundaries (Quinteiro 2018). In caving operations, the footwall drifts are considered the arteries for the mine's cash flow. Therefore, their ongoing stability is of crucial importance. If the access deforms to such an extent at which it is no longer serviceable, ore production and cash flows are halted. This can result in serious implications for companies; notably in lost production revenues and rehabilitation expenditure. Stability is affected by a number of parameters including rock properties, mining-induced stresses, thickness of weak zones and the location of the drifts with respect to weak zones. For this example, drifts are situated in a weak rock mass zone, with different locations relative to the active mining front examined and modelled probabilistically.

The further the drift is moved away from the orebody, mining-induced stresses decrease more, lessening the effects of deformation. Hypothetically, a quick decision could be made to simply place the drift far away from the active mining front. In reality, decisions are not this simple. The problem presented is determining the optimal location to place the footwall drifts. Positioned close to the orezone is good for loader tramming efficiency and results in decreased development costs. However, it is often associated with poor stability and requires large rehabilitation expenditure. Further away from the orezone the opposite begins to occur. Assigning a Factor of Safety (FS) to different development distances is not helpful as this cannot be related to a reasonable risk-based decision criterion. If the safety limit is set too high, companies incur excessive development costs and suffer productivity reductions. The big picture must be examined in order to make the right decision in this case and take into account deformation risk, rehabilitation expenditure, production disturbances, and the optimal level of development metres. Joughin (2017) has created a good approach, with the incorporation of probability theory and visual outputs of economic consequence. However, he does not specifically look at the time value of money or development expenditure as a complete risk decision criterion, which is something that is implemented in this model. Money which is spent today does not have the same value in the future, and there exists a significant opportunity cost with this capital having the potential to be invested in other business areas and earn a rate of return. A company return on equity is used to approximate this, with summated deformation risk losses brought forward and compounded over the life of the mining level.

This paper, therefore, advocates a risk-based design approach, focusing on the economic consequence outcomes. A risk-based design approach is one in which drift opening acceptance criteria is defined in terms of risk. Both numerical and probabilistic outcomes are created in order to assess and evaluate risk exposures. Results are then conveyed with the aid of risk matrices, the likes of which are used daily in mine sites worldwide. Data from large sublevel caving (SLC) operations are used to construct a damage model for a footwall access, highlighting the applicability and versatility of the risk-based design approach to failure modelling. This paper considers the financial future value of deformation damage and assesses this over the life of the mining level. This is done with the aim of representing the lost opportunity cost the company may bear in the event of failure, which can be related to development expenditure as a risk-based design criterion.

2 Defining risk criteria

Engineering design must be performed according to a predefined acceptance criteria which captures the design objectives for a project. For mining operations, it is argued that these design acceptance criteria need to be stated in terms of risk (i.e. risk-based design). Final decisions in mining operations are based on both risk and financial cost, rather than probability distributions. Joughin et al. (2016) states that, “design acceptance criterion based on probability of failure has little meaning within the mining context as the important factor that needs to be managed is not failure but risk”. Failure with no adverse consequence is far preferred to unnecessary stability created at a high cost (Wesseloo & Joughin 2018).

The company risk profile determined by management therefor determines the design acceptance levels. High probability of occurrence failures with low consequence and low probability failures with large consequence are both considered within the company risk profile. Depending on the drive being assessed, different risks and controls could be tolerated. Figure 1 provides an overview of the interlinked processes between FS, Probability of Failure (PF) and risk as design acceptance criteria within the design process.

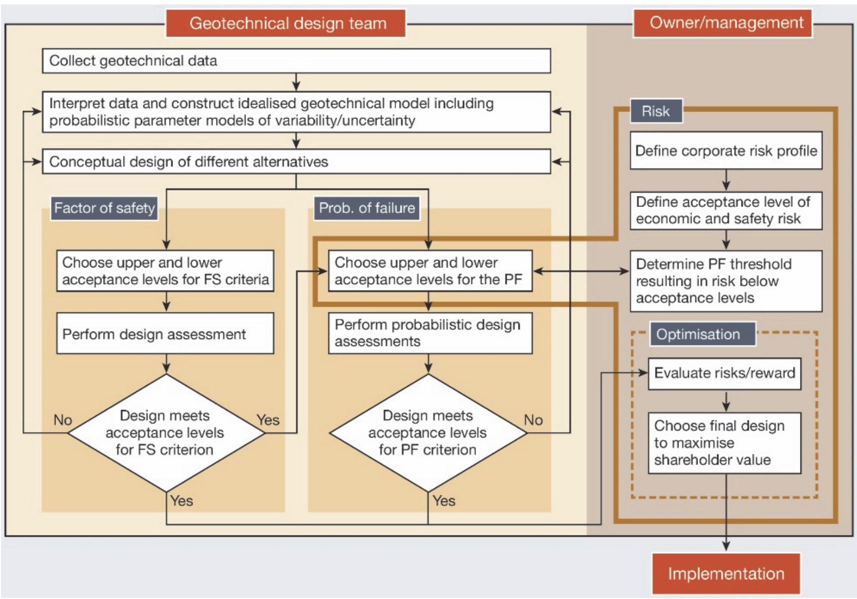

Figure 1 Relationship between FS, PF and corporate risk throughout the design process (Wesseloo & Joughin 2018)

The owner/management process flow is integral and should form a strong part of the design process. Decision-making is often limited to the engineering department, where risks are accepted based on predefined levels and often without quantification. Particularly for the footwall access, this is not acceptable. The risk profile should be quantified in detail. In such cases, the design acceptance criteria process should be rigorous and dictated by managerial oversight and involvement of the company risk profile.

Risks also need to be conveyed in an effective way across the organisation. Most companies currently utilise risk matrices as risk communication tools, with economic risk tolerances varying depending on the size of the operation. Likelihood categories can be described in terms of probabilities, time periods or simple qualitative descriptions (Joughin 2017). Applying different likelihood boundaries will influence the interpretation of risk levels and consequences. Many authors have suggested using risk matrices for risk evaluation (Brown 2012; Abdellah et al. 2014; Contreras 2015; Joughin et al. 2016). However, the subjective nature of these matrices can lead to varying interpretations. To minimise incorrect interpretations, it is suggested to utilise a matrix that is familiar and relevant to your particular organisational situation.

For this paper, a modified version of the risk matrix presented by Joughin (2017) (Figure 2) was used, outlining severity and likelyhood occurrence in greater detail. This enables a more practical interpretation of likelihood, but it is essential to convert probabilities into normalised expected frequencies (Joughin 2017). For this case study, a company risk tolerance for the footwall access drives has been assumed as low for risk likelihood and low–medium for consequence.

			Severity of consequences				
	Assets/Business disruption		No operations disruption, minimum cost for repair	Possible brief disruption	Operations partly down, can be restarted	Partial loss of operation, significant rehab	Total loss of operations/shut down for >4 weeks
	Consequence		Insignificant	Minor	Moderate	Major	Catastrophic
	Cost		cost >$1,000	cost>$10,000	cost>$100,000	cost >$1,000,000	cost > $10,000,000
Likelihood			A	B	C	D	E
Incident is expected to occur in most circumstances at the location during the lifecycle	Daily to weekly	5	HIGH	HIGH	EXTREME	EXTREME	EXTREME
Incident will probably occur in most circumstances at the loction during the lifecycle phase	>Monthly	4	MEDIUM	HIGH	HIGH	EXTREME	EXTREME
Incident could occur at the location during the lifecycle	>Annualy	3	LOW	MEDIUM	HIGH	EXTREME	EXTREME
Incident is unlikely, but possible to occur at the location during the lifecycle	>1 in 10 years	2	LOW	LOW	MEDIUM	HIGH	EXTREME
Incident is unlikely but may occur under exceptional circumstances	Rare	1	LOW	LOW	MEDIUM	MEDIUM	HIGH

Figure 2 Risk matrix (Joughin 2017)

3 Practical application

The risk-based approach allows engineers to assess the viability of their infrastructure designs using a risk-based design criterion, outlined in Sections 1 and 2. Designs can then be compared on the basis of risk exposure whilst considering the company risk profile, development costs, production losses, and expected rehabilitation expenditure. In this paper, the stability of footwall drives at different distances from the orebody is assessed in a probabilistic manner. From this, the probability and expected frequency of rehabilitation can be assessed over the life of the mining level. This information, together with the company risk profile forms the basis for the economic failure model. The economic model takes the expected frequency and length of failure, creating an economic dollar value output, based on lost production revenue and rehabilitation expenditure. The time value of money is then considered, applying an annual rate of return to the rehabilitation costs.

Probabilistic modelling is important as this enables engineers to account for the uncertainty (risk) in the geotechnical domains in which mining companies operate. These domains are non-homogenous in nature, with lithology and rock mass properties potentially differing with each metre advance. Currently, this uncertainty is not always well accounted for in the design of underground mine openings. By incorporating this modelling approach, the uncertainty is better incorporated whilst providing management with an understanding of the potential scenarios they may encounter in the underground operations.

When examining the cost implications of failure, the time value of money and opportunity costs should be considered. Incurred expenses could be beneficially utilised for machinery or infrastructure investment that would generate an appropriate rate of return for the company and benefit mining operations. To do so, the potential failure costs are calculated using the economic model and expected frequencies of occurrence. This is known as the risk premium, which is assessed and normalised over the life of the mining level. The risk premium can then be inflated using an appropriate rate of return and a future value formula. This is valuable information, as it allows management to make estimates of their potential profits. The final risk premiums can then be compared to yearly development costs for the proposed footwall drift being considered.

We feel this approach provides great benefits for organisations. The risk-based design criteria enable management to look at the big picture in a manner that is relevant and customisable to different operational situations. At the end of the process, economic consequences can be plotted onto company risk matrices. This visual output can then be compared to management-defined risk exposures, alongside total economic consequences, in an easily conveyable manner that will be relatable to stakeholders. The risk-based design criteria enables management to look at the big picture in a manner that is relevant and customisable to different operational situations. Designs can then be selected based on this criterion and assessed on the basis of lowest actuarial cost.

We performed analysis using data from published studies to illustrate the value of the risk-based design approach to the mining industry. Data was gathered from published studies (Idris et al. 2013; Edelbro et al. 2012) on underground SLC operations. From a practical and serviceability point of view, we define the maximum allowable strain limit before rehabilitation is required at 7%. This relates to about 400 mm tunnel convergence for the 6.5 m wide excavations considered in this application.

4 Damage risk model

The following steps summarise the damage model design methodology. Each step should be reviewed and assessed on a case-by-case basis dependant on individual operating circumstances.

1. An existing SLC operation is examined.
2. The risk context with key inputs and outputs needs to be explicitly determined.
3. Inputs:
   a. Rock mass properties.
   b. Mining-induced stressed.
   c. Footwall drift location (variable l_{FWD}) relative to weak lithological zone.
4. Three scenarios will then be modelled, varying l_{FWD} in 2D FE software (Rocscience Inc 2015) to obtain damage results.
5. A criterion of 7% strain is applied, exceedance implying the drift is no longer serviceable and is assumed as ‘failed’.
6. PF is calculated, creating probabilistic outputs.
7. Probability of tunnel segment failure can then be calculated.
8. The likelihood of (N) segments of tunnel failing is then calculated.

9. Risk is then quantified.
10. An economic consequence assessment is then conducted. Consequences can be calculated considering failure length, loss of production revenue and rehabilitation costs. This is compared to the costs of initial level development.
11. The lowest risk is then selected, with the risk re-assessed and expressed with the term 'lowest actuarial risk'.

5 Evaluating economic risk due to stress damage

The input data and associated uncertainty is described in Section 5.1, followed by the probabilistic numerical analysis (Section 5.2). Frequency and the extent of excessive damage are determined in Section 5.3.

In Section 5.4, total economic risk is evaluated and discussed. This considers the cost of rehabilitation (removing failed rock and re-supporting), lost revenue as a result of interrupted production, and the cost for new development metres. The company risk profile has been defined as low to medium for the footwall access drive, defined in Section 2.

5.1 Input data

Scenarios were modelled using data from published studies (Idris et al. 2013; Edelbro et al. 2012). The data was modified using systematic, broad assumptions for practicality. Significant figures were reduced and post-peak parameters were assumed at half their respective peak counterparts, with the exception of Young's modulus (Table 1). Poisson's ratio was assumed at 0.25. The mine experiences deformation resulting from the interface of weak rock mass under the influence of mining-induced stresses. This influence was simulated via varying the development distance from the orebody contact and the accompanying stresses (Table 2).

Table 1 Rock mass material properties and variability (Idris et al. 2013)

Parameters	Weak rock mass		
	μ	σ	Post-peak
E_m (GPa)	10	3	10
c (MPa)	3.2	0.4	1.6
σ_t (MPa)	0.2	0.1	0.1
Φ (°)	40	5	20

Mining-induced stresses due to the applied production method were assumed for the purpose of the study by referring to published records (Edelbro et al. 2012).

Table 2 Mining-induced stresses as footwall drift recedes from orebody contact (Edelbro et al. 2012)

Distance from orebody contact (m)	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)	Angle (°)
10	78	35	20	8
40	65	30	15	12
85	53	27	12	15

Angle (°) = degrees between maximum principal stress and horizontal

The access drive was assumed to be fully enclosed in weak rock mass. This was selected to model the worst case scenario that could occur during planning decisions. Figure 3 shows the modelled scenarios.

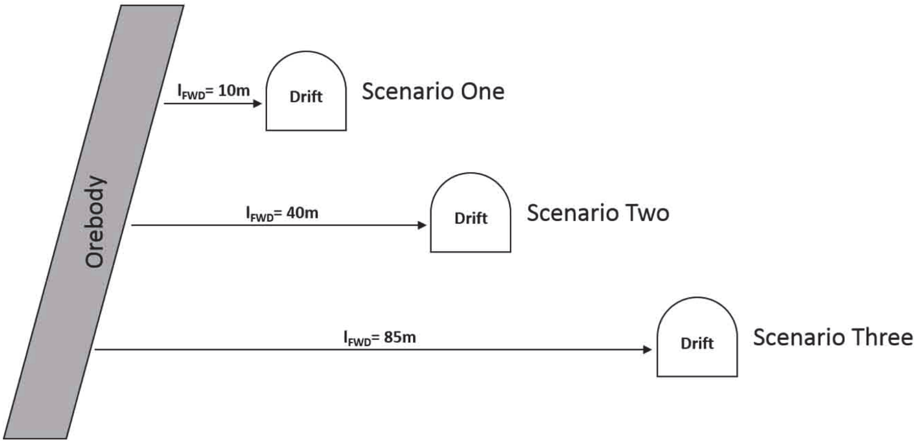

Figure 3 Modelling scenarios for footwall access and orebody contact separation

5.2 Probabilistic stress analysis

Elastoplastic stress analysis was conducted using 2D FE software (Rocscience Inc 2015). Input data from Section 5.1 was modelled probabilistically using the point estimate technique. Figure 4 shows the model geometry used for the initial setup.

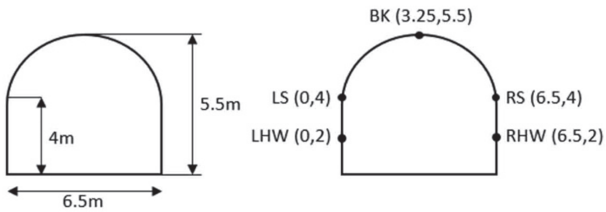

Figure 4 Numerical model setup

Anticipated deformation can be estimated by applying a lognormal distribution to the modelling output data (Table 3). In this instance, Palisade's @RISK (Palisade 2016) was used. Cumulative probability distributions for drift deformations can then be calculated, as presented in Figure 5. In this study, half wall closure was considered as the main point of concern. Cumulative strain plots of tunnel convergence for the half wall reference points were created, ascertaining the level of strain experienced in relation to the design constraint.

Table 3 Deformation modelling results

RP	Deformation (mm)					
	Scenario 1		Scenario 2		Scenario 3	
	μ	σ	μ	σ	μ	σ
LHW*	176	62.1	136	48.3	97.6	34.6
RHW*	177	61	131	49	96.4	32.4
LS*	166	58.4	120	43.4	82.8	31.7
RS*	145	50.4	105	35.7	75.8	23.9
BK*	292	97.4	206	69.3	147	49.9
RP = reference point, μ = mean value, σ = standard deviation						
Scenario 1 = 10 m from mining front Scenario 2 = 40 m from mining front Scenario 3 = 85 m from mining front						

*Defined in Figure 4.

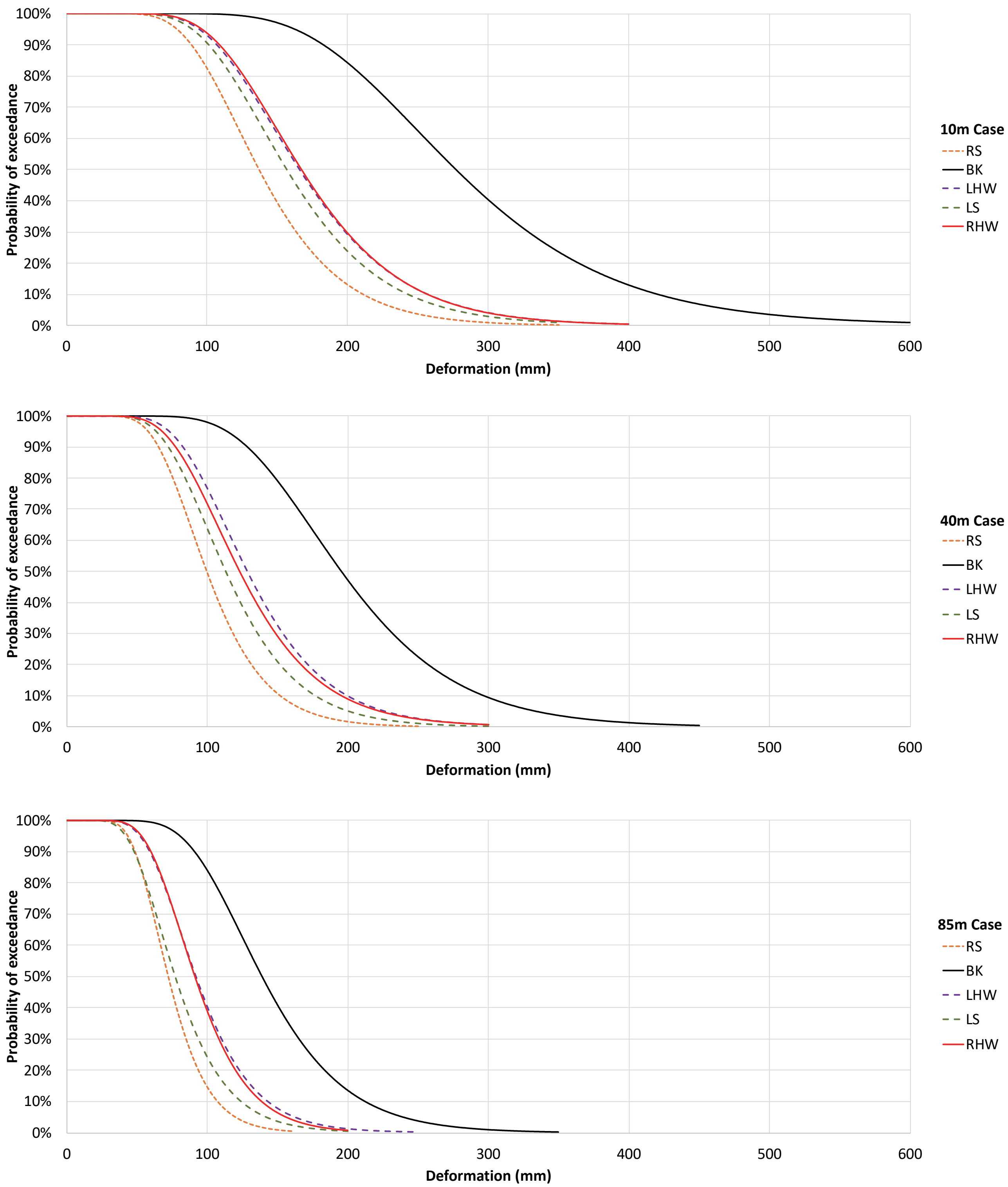

Figure 5 Cumulative probability distributions of deformation (footwall access drive)

5.3 Extent and frequency of deformation estimation

Continuing from the works of Joughin (2017), it is necessary to determine the frequency of damage occurrence that may occur over a given length of the access.

The total length (L) of the footwall access being considered would not normally be affected all at the same time. In practice, the potentially affected length (l_p) at a given time will be a function of the mining layout, sequence and stress influences (Figure 6). For this particular case, a development model assumption was created. A transverse mining approach was adopted, occurring over two levels, each ~400 m in length with ~50% exposed at any one time. The two-level completion period was selected as three years. Therefore an l_p of 200 m was selected. The selection of (l_p) will be different for each case being examined.

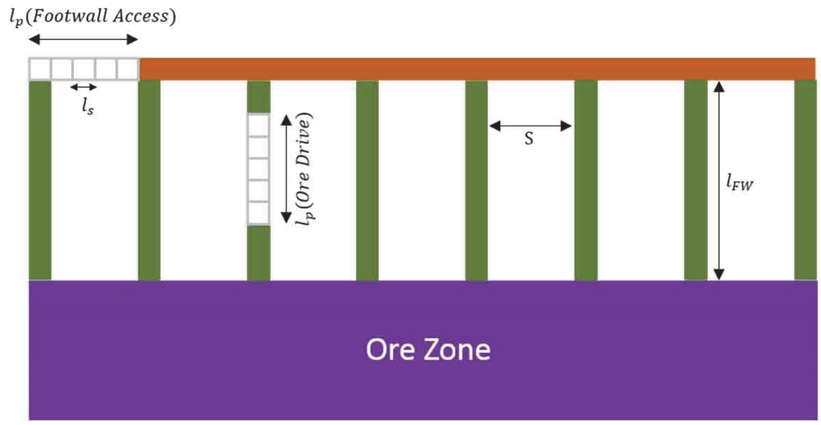

Figure 6 Potential damage zones highlighting l_p and l_s

For example, the access in many mines will usually experience less significant stress changes compared to an oredrive, due to its locale being further away from the mining front. The probability of exceeding deformation criteria is expected to be lower. However, the potentially affected lengths and associated impacts may be greater. The l_p selection will always be a subjective matter and will vary with each designer, hence it is necessary to utilise good engineering judgement and test different l_p values to assess the engineer's selection influence on the model.

This l_p is then further sub-divided into short tunnel segment lengths (l_s), which represent potential damage segments and variability in rock mass characteristics. Since it is difficult and costly to predict conditions beyond drift boundaries, it is deemed prudent that the minimum l_s be the width of the drive being assessed.

The probability (p) of exceeding the deformation criteria is determined using the methods in Section 5.2 (Joughin 2017). The probability of exceedance is then applied to the affected length (l_p). As detailed by Joughin (2017), the segment length may be either completely or partially affected by excessive deformation. Figure 7 shows scenarios of possible damage over l_p for a given p.

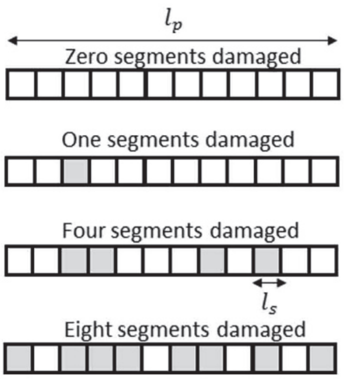

Figure 7 Damage scenarios over the affected length l_p

The probability *Pr(k,p,n)* of exactly *k* segments being excessively damaged can be estimated using the binominal distribution:

$$\Pr(k,p,n) = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \tag{1}$$

where n is the total number of tunnel segments (rounded to nearest integer) and is calculated as follows:

$$n = {}^{l_p}\!/_{l_s} \tag{2}$$

The cumulative form of the binomial distribution is then calculated, which represents the probability Pr(>k) of more than k segments being damaged:

$$\Pr(\geq k,p,n) = \sum_{i=k}^{n} \frac{n!}{i!(n-i)!} p^i (1-p)^{n-i} \tag{3}$$

This can be found as an inbuilt function in most statistical packages. However, care needs to be taken as the default form is usually cumulative ascending ($\Pr(\leq k,p,n)$.

The length of damage, l_d, for a given k, l_s and l_p is then:

$$l_d(k,l_s) = l_s k \tag{4}$$

Figure 8 shows the cumulative probability damaged tunnel lengths, for a footwall access located 10 m from the mining front with an l_p = 200 m, l_s = 6.5 m and p = 0.114.

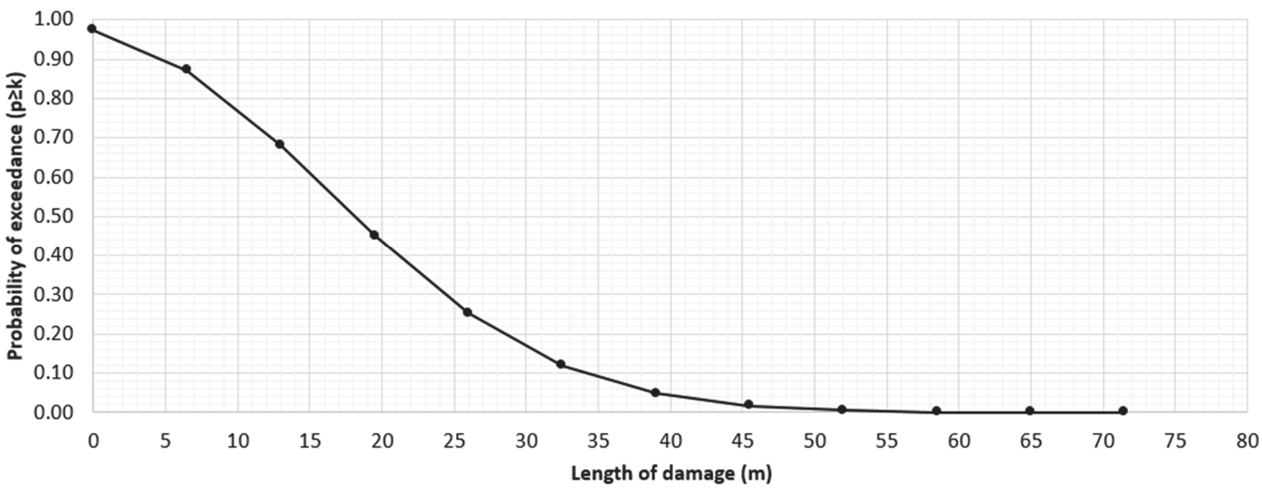

Figure 8 Cumulative probability damaged tunnel lengths for 10 m case

During the life of the level development, the entire length L of the footwall access could be affected at some stage in time. The number of potentially affected lengths (N) is inferred by:

$$N = \frac{L}{l_p} \tag{5}$$

The expected frequency of occurrence can then be estimated as follows:

$$\mathrm{F}(\geq k, p, n, N) = \mathrm{Pr}(\geq k, p, n)\, N \tag{6}$$

This can then be normalised over the duration of mining on the levels of interest (T).

$$\mathrm{F}(\geq k, p, n, N, T) = \frac{\mathrm{Pr}(\geq k, p, n) N}{T} \tag{7}$$

The time unit for normalisation is case specific and could be days, weeks, quarters or years (Joughin 2017). In this example, frequency was normalised by three years as per the level completion time (Figure 9). The input parameters specific to this footwall access case are listed in Table 4.

Table 4 Input parameters for footwall access case study damage analysis (10 m case)

Parameter	Footwall access
Total length (L)	800 m
Proportion of L at risk at any one time	50%
Potentially affected segment (l_s)	6.5 m
Potentially affected length (l_p)	200 m
Number of potentially affected lengths (N)	4
Number of segments (n)	~30
Duration (T)	3 years
Probability of exceeding deformation criteria (7% strain)	0.114

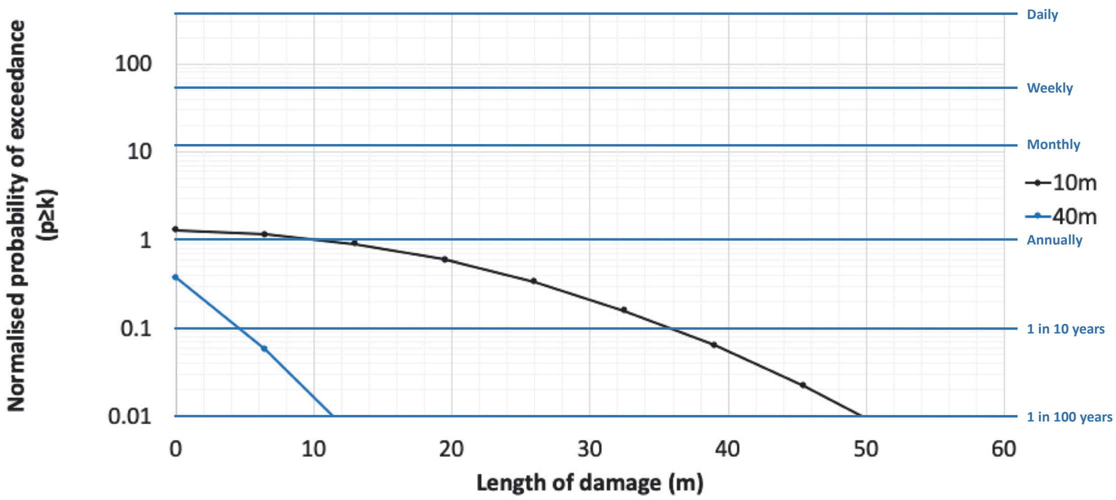

Figure 9 Cumulative normalised (years) expected frequency damage length distributions for 10 and 40 m case

5.4 Economic risk evaluation

In monetary terms, the risk premium (the expected cost of failure) is defined as the product of the cost of failure and the failure probability. Failure probabilities are directly influenced by the level of safety adopted in designing, developing and operating mining infrastructure. Financial economics and safety follow an inverse relationship. Generally speaking, increasing safety implies greater costs to an organisation (Beck & Gomes 2012). Therefore, a trade-off presents itself and an informed risk-based decision needs to be implemented. Economic losses attributed to rock deformation have already been addressed in literature (Joughin et al. 2012; Abdellah et al. 2014; Joughin et al. 2016). The most significant economic costs are remediation of the damaged tunnel sections and the lost production output from the affected area due to inaccessibility. This paper has found, for the proposed caving bulk mining method, that the production losses far outweigh the rehabilitation costs incurred. A new approach is considered for the three cases, introducing a method to calculate and compare an approximation for moving the footwall development further out from the mining front. Drawing from the world of finance, money spent today does not have the same value in the future. Rehabilitation costs (sunken costs) could be invested elsewhere at an appropriate rate of return. Therefore, this introduces a significant opportunity cost component when analysing risk and deformation results. Particularly over the life-of-mine, the opportunity cost can be significant and have real upside potential if the risk is mitigated and capital is better employed. For the proposed scenario, the summated normalised yearly cost of failure is used. This is accrued and brought back to the beginning of the mining level's life (at the decision-making process stage). This is then compounded over the life of the level (three years in this case) to present an opportunity cost and a possible level of return had this capital been invested at the company's return on equity rate. It is an attempt to assess the level of risk in a simplified manner, whilst also considering the possible extra value that is forgone by allowing failure to occur.

To ascertain rehabilitation costs, it is suggested to use estimates of the cost per metre (c_r) and rate (r) of rehabilitation using data from previous tunnel repairs. The total cost of rehabilitation $C_r(k,l_s)$ and duration $t_r(k,l_s,r)$ of rehabilitation can then be estimated using $l_d(k,l_s)$ (Section 5.3) as follows:

$$C_r(k, l_s, c_r) = l_d(k, l_s)c_r \quad (8)$$

$$t_r(k, l_s, r) = \frac{l_d(k,l_s)}{r} \quad (9)$$

After conducting a quick survey of general rehabilitation costs, Table 5 contains estimates of rehabilitation costs, with the following input values used in this example:

- Cost per metre of rehabilitation: c_r =AUD 10,000/m.
- Rate of rehabilitation: r = 2 m/day.

Table 5 Rehabilitation cost estimates for changing rock types and mining methods

Mining method and rock type	Case multiplier	Rehabilitation cost estimate c_r (AUD/m)
Base case: hard rock, non-seismic	1	2,000
Hard rock, seismic	2–5	4,000
Hard rock, caving	5	10,000
Soft rock, seismic and caving (UCS ≤80 MPa)	8–10+	16,000

During rehabilitation, production is affected to varying extents depending on the purpose of the drift. Rehabilitation of the main footwall access would always affect the full production from these areas and will have an immediate effect. Rehabilitation of a stope drive would only effect a percentage of production, and there may be some flexibility (t_f) in the schedule to cater for this before effects are felt. The lost production time can be estimated as follows:

$$t_p = t_r - t_f \quad (10)$$

The following model can be used to estimate the potential production loss per damaging incident as a function of length of damage:

$$C_P = t_p \cdot c_p \cdot (1 - a) \cdot m \cdot b \quad (11)$$

where:

c_p = revenue per tonne mined (AUD 65/tonne utilised).

a = direct cost of production as a proportion of revenue (0.5 utilised).

m = daily production from the level (3,616 tonnes).

b = proportion of daily production affected (1 utilised).

$$C_{Sunk} = C_p + C_r \quad (12)$$

C_{Sunk} represents a company's sunken costs for rehabilitation. This is capital that in effect, if the scenario was better managed, did not need to be deployed. The capital could have been invested in other areas of business, earning the company minimum return on equity rate. A future value formula can be used to approximate this.

$$FV = PV(1+i)^t \quad (13)$$

where:

i = annual return on company equity.

t = duration of investment (years).

FV = future value.

PV = present value.

For the deformation case, the sunken risk adjusted cost for each failure occurrence is represented as:

$$C_T = C_{Sunk}(1+i)^t \quad (14)$$

Using the cumulative normalised expected frequency damage length distributions of Section 5.3 and the economic model, cumulative normalised expected frequency distributions of economic loss can be presented using the risk matrix from Figure 2. Risk profiles have been determined for the footwall access scenarios considered (Figures 10 and 11). Note that severity is greatest for the 10 m case, due to the amount of production effected by deformation. The 80 m case did not exceed strain criteria, and was omitted from consideration. Rehabilitation costs range from minor to moderate, whilst production losses range from moderate to major depending on days lost.

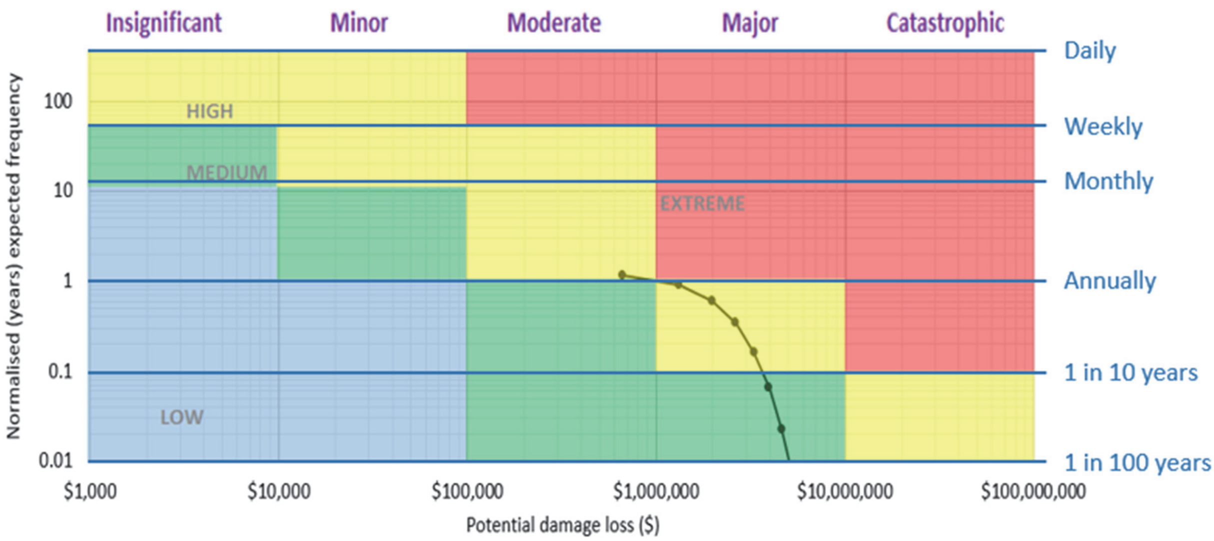

Figure 10 Footwall access ramp risk profile for 10 m distance from mining front

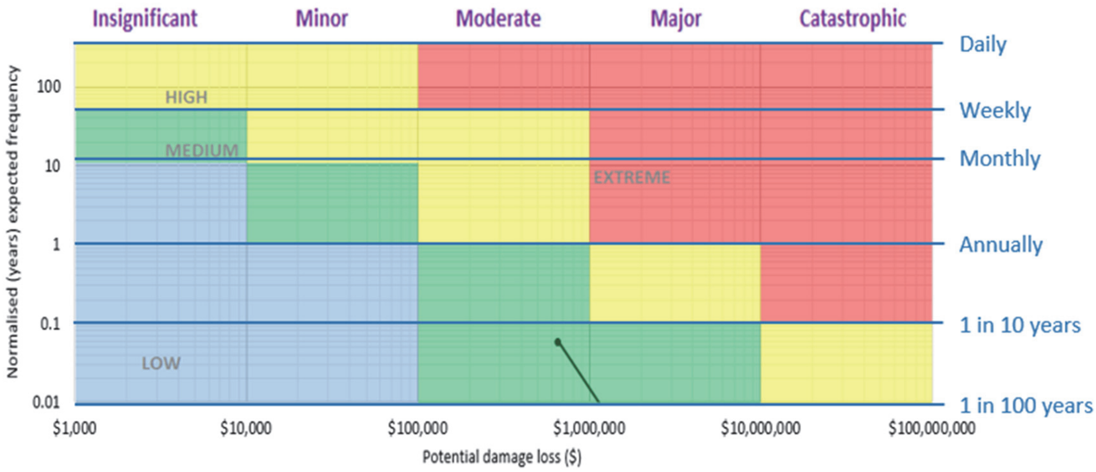

Figure 11 Footwall access ramp risk profile for 40 m distance from mining front

Designers can then approximate the development length (l_{dev}), haulage costs (C_H), development time (t_D) and total cost for extra development (C_D) using the following equations:

$$l_{dev} = length\ of\ development\ (m) = \frac{L \cdot l_{FW}}{s} + L \tag{15}$$

where:

s = oredrive spacing (m).

l_{FW} = distance from mining front (m).

L = level metres active at any time.

For this example, s was assumed as 22.5 m (Shekhar et al. 2017). Development haulage costs can be approximated as follows:

$$C_H = C_m \cdot (l_{dev} \cdot E_A \cdot \rho) \tag{16}$$

$$C_D = l_{dev} \cdot D_C + C_H \tag{17}$$

where:

R_d = development rate (m/day).

D_C = development cost ($/m).

E_A = excavation area (m^2).

C_M = unit haulage cost ($5/t).

p = density.

C_D = total development cost.

C_H = total haulage cost.

The total cost can be assessed below, following a modified model from Beck and Gomes (2012) and an overall risk-based decision made.

$$C_{Total} = C_{Development} + C_{Operation} + C_{Monitoring} + C_{Closure} + \sum C_{Failures} \cdot F(\geq k, p, n, N, T) \tag{18}$$

Given that the costs of closure, monitoring, and operation can be difficult to define, the formula can be simplified for initial design considerations. If the drive being considered is assumed to have constant operational, inspection, and closure costs, it can be simplified to:

$$C_{Total} = C_D + \sum C_T \cdot F(\geq k, p, n, N, T) \tag{19}$$

Input parameters specific to the access ramp case are listed in Table 6.

Table 6 Input parameters for the development costing analysis

Parameter	Footwall access value	Source
D_C (\$/m)	6,500	(AusIMM* 2012)
E_A (m^2)	30	Derived from numerical model
C_M (\$/t)	5	Estimated from (Poxleitner 2016)
p (t/m^3)	2.7	Assumed
s (m)	22.5	(Shekhar et al. 2017)

*The Australasian Institute of Mining and Metallurgy

Variable $\sum C_T \cdot F(\geq k, p, n, N, T)$ can be regarded as the yearly risk premium for the given scenario decision. Combining this with level development costings, an informed risk-based decision can be made. This is where determining the company's initial risk tolerance and profile at the beginning of the exercise is so important. A subjective decision will always need to be made, containing a great deal of engineering judgement. Comparing the risk level plots from Figures 10 and 11 with the company's risk profile can be an important determinant in deciding whether extra capital allocation is warranted or not, in order to reduce risk to management-approved levels.

6 Economic discussion

6.1 Results

Calculating C_{Total} from Section 5.4 designers can begin to analyse the different scenario options and create informed, risk-based decisions.

Table 7 shows the estimated development costs for each scenario (C_D) alongside risk premiums (C_T) and summated total costs (C_{Total}). These costs can then be compared with the risk profiles from Figures 10–11.

Table 7 Economic comparison

Scenario	Yearly development costs C_D (\$)	Yearly risk premiums C_T (\$)	Yearly total costs C_{Total} (\$)
One (10 m)	2,659,703	4,991,551	7,651,255
Two (40 m)	5,114,814	46,475	5,161,290

Care needs to be taken when extrapolating financial results into the future. The important variable is that of time and normalisation. In this instance, failure is only considered for the basis of the initial design choice comparison and has been yearly normalised, so a duration value (t) of three is appropriate. If these cost premiums were extended into the future (e.g. net present value modelling), the time and discount rate variable will vary, dependent on the time occurrence of the failure relative to mining level life. The future value option proposed applies a standard duration of capital employment. This correlates to a company expecting a given level of return from an investment within a defined time period (life of the mining level). This would set the value of (t) at a defined level. As failures have been predicted, it is reasonable to record them in entirety from t = 0 and determine their future values.

A company return on equity (i) of 14% was assumed for this case. The return value (i) along with (t) can play a large role in the final economic outcome depending upon whether an aggressive or conservative modelling approach is selected.

In this case, scenario one is suggested to be omitted as the risk profile falls in the high range and damage costs of ~USD1,000,000 occur on a near annual basis. This lies outside the company's risk tolerance, defined in Section 2.

Scenario two lowers the risk profile significantly, However, it incurs greater development costs. The result is not surprising, given the increased distance from the mining front and the capital-intensive development nature of caving operations. As mentioned, scenario three was omitted due to not registering a p value and the excessive development costs required. Good engineering judgement needs to be utilised to make an informed decision in this instance. It is apparent that the best case scenario for the location of the footwall access drift lies somewhere in between these points of reference. For the purpose of the case, assuming decisions can only be made on the three available options, it is suggested scenario two be progressed as it falls in line with the company's risk profile, whilst also maintaining an acceptable level of development capital expenditure and total costs. Future optimisation and coding work will be needed to determine the true optimal case that balances both risk exposure and development expenditure.

7 Conclusion

This proof of concept study highlights the versatility and practical applicability of the risk-based design process when considering geotechnical uncertainty. Stress and model uncertainty will always remain a challenge in engineering designs and an amount of subjective engineering judgement will always be necessary. The evaluation of risk during the design process will help ensure your objectives are aligned with those of upper management and the company risk profile. The design team must ensure they are accounting for the inherently variable nature of mining operations and the lack of complete datasets in order to prepare for the variety of scenarios that may occur.

It is also useful to be able to predict and visually convey the potential financial impact for different designs. The economic failure model is flexible in its design, able to be tailored to individual cases with little effort. The risk matrix output ensures a practical and relatable result that can be readily conveyed to key stakeholders in the mining organisation.

Future optimisation work will be needed to determine the true optimal case that balances both risk exposure and development expenditure. The implications of safety risk should also be included, creating a full suite design tool to assess underground excavations on both an economic cost and potential injury/public relations consequence base.

Acknowledgement

Thanks are extended to the various geotechnical teams consulted that generously offered their time to discuss rehabilitation techniques, timeframes, and rough estimates.

References

Abdellah, W, Mitri, HS, Thibodeau, D & Moreau-Verlaan, L 2014, 'Risk indexing tool for mine planning', *Journal Of The Southern African Institute Of Mining And Metallurgy*, vol. 114, pp. 435–444.

AusIMM 2012, *Cost Estimation Handbook*, AusIMM, Melbourne.

Beck, AT & Gomes, WJDS 2012, 'A comparison of deterministic, reliability-based and risk-based structural optimization under uncertainty', *Probabilistic Engineering Mechanics*, vol. 28, pp. 18–29.

Brown, ET 2012, 'Risk assessment and management in underground rock engineering—an overview', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 4, no. 3, pp. 193–204.

Contreras, LF 2015, 'An economic risk evaluation approach for pit slope optimization', *Journal Of The Southern African Institute of Mining And Metallurgy*, vol. 115, pp. 607–622.

Edelbro, C, Sjoberg, J, Malmgren, L & Dahner-Lindqvist, C 2012, 'Prediction and follow-up of failure and fallouts in footwall drifts in the Kiirunavaara mine', *Canadian Geotechnical Journal*, vol. 49, no. 5, pp. 546–559.

Idris, MA, Basarir, H, Nordlund, E & Wettainen, T 2013, 'The probabilistic estimation of rock masses properties in Malmberget mine, Sweden', *The Electronic Journal of Geotechnical Engineering*, vol. 18, no. B, pp. 269–287.

Joughin, W, Jager, A, Nezomba, E & Rwodzi, L 2012, 'A risk evaluation model for support design in Bushveld Complex underground mines: part I-description of the model', *Journal of The Southern African Institute of Mining And Metallurgy*, vol. 112, no. 2, pp. 83–94.

Joughin, W, Muaka, J, Mpunzi, P, Sewnun, D & Wesseloo, J 2016, 'A risk-based approach to ground support design', *Proceedings of the Eighth International Symposium on Ground Support in Mining and Underground Construction*, Luleå University of Technology, Luleå.

Joughin, WC 2017, 'Dealing with uncertainty and risk in the design of deep and high stress mining excavations', in J Wesseloo (ed.), *Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 489–507.

Palisade 2016, *@RISK*, computer software, Palisade Corporation, Ithaca, https://www.palisade.com

Poxleitner, G 2016, *Operating Costs for Miners*, SRK Consulting (Canada) Inc., Sudbury, viewed 18 February 2018, https://www.srk.com/en/publication/na-operating-cost-miners

Quinteiro, C 2018, 'Design of a new layout for sublevel caving at depth', in Y Potvin & J Jakubec (eds), *Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 433–442.

Rocscience Inc. 2015, *RS2*, version 9.08, computer software, Rocscience Inc., Toronto, https://www.rocscience.com/software/rs2

Shekhar, G, Gustafson, A & Schunnesson, H 2017, *Loading Procedure and Draw Control in LKAB's Sublevel Caving Mines: Baseline Mapping Report*, Luleå University of Technology, Luleå.

Wesseloo, J & Joughin, W 2019, internal document, Australian Centre for Geomechanics, Perth.