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Estimating the probability of unsatisfactory performance associated with the instability of mine developments

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ABSTRACT

Mine developments are the main access to extract tabular ore deposits in deep underground mines. Therefore, their stability is considered the principal priority during the mine production plan. The success of ore extraction mainly depends on the stability and serviceability of mine developments. Mine development instability is expensive and is a risk to personnel and equipment and in turn, it raises operational costs (e.g, repair costs, slashing, rehabilitation costs, costs of adding secondary support, miners wages and delay of production) (Ellefmo, and Eidsvik, 2009; Abdellah et al. 2014a; 2014b; 2014c). This paper aims to develop a hybrid approach in which deterministic numerical modelling is integrated with probabilistic methods to estimate the probability of unsatisfactory performance (e.g. rating and ranking) associated with the instability of mine developments with respect to mining sequences adopting Rosenblueth's Point-Estimate Method (RPEM). A three-dimensional, elastoplastic, finite difference model (FLAC3D) is created (Itasca, 2009). The results are presented and categorized with respect to the probability of instability and the mining stage.

KEYWORDS: Mine developments; numerical modelling; Rosenblueth's Point-Estimate Method (RPEM); probability of unsatisfactory performance

1. INTRODUCTION

Many Canadian metal mines adopt a sublevel stoping mining method with delayed backfill, as shown in Figure 1. In this method, ore is mined out into stopes (blocks), which are drilled and blasted. The blasted ore from each stope is mucked out with loaders and transported from a draw point to a nearby ore pass or dumping point. Mine developments (e.g., haulage drifts, cross-cuts and their intersections) are the only access where loaders and/or trucks travel through on multiple levels. Therefore, their serviceability must remain active for a few years (e.g., production plan of the mine) (Wei et al., 2012; Zhang and Mitri, 2008). The following five parameters should be considered in the design process: safety, serviceability (e.g., quality of technical solution), economics (e.g., cost), environment, and rockmass properties. For example rockmass properties alone are complex and are associated with uncertainty in deep underground mines. These five factors should be maintained and combined together in the decision-making process.

Consequently, wrong decision may lead to unwanted risks. In order to facilitate decision-making, probabilistic analysis should be adopted (Einstein, 1996; Sturk et al., 1996; Abdellah et al., 2014c). The stability performance of mine developments could be evaluated by adopting analytical, empirical, and numerical modelling techniques. The analytical methods such as those provided by Kirsch (1898), Bray (1977), Bray and Lorig (1988), and Ladanyi (1974) cannot provide adequate solutions for complex mining problems. Empirical methods such as the stability graph method, have become widely used in Canadian underground mines. These methods are based on the past experiences and rockmass classification systems.

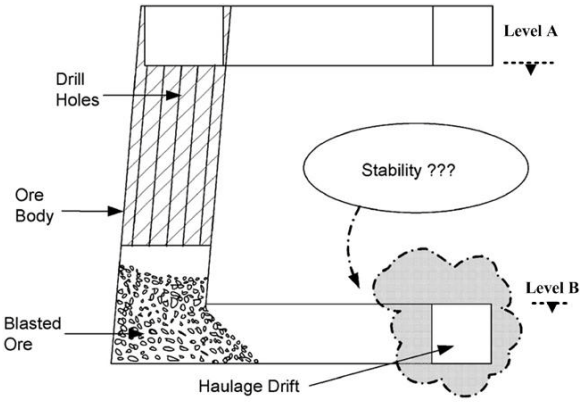


Figure 1: Section view shows sublevel stoping mining method

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They employ certain geomechanical characteristics of the rockmass to provide guidelines on stability performance and to determine the rock support requirements. However, these methods cannot take all the important influence factors into account. Therefore, numerical methods have become widely accepted in mine design and feasibility studies.

Numerical methods have the potential not only to solve complex mining problems, but also to help engineers and researchers better understand and assess failure mechanisms, estimate geotechnical risks, and design rock reinforcement systems more effectively. Numerical analyses can be performed deterministically or probabilistically. In a deterministic analysis, the average values of the rockmass properties are used as input parameters, and a unique model result is obtained. However, no information can be obtained about the likelihood of failure due to the inherent variability of model input parameters. Thus, probabilistic methods are employed to carry out stochastic analyses to overcome this shortcoming. The uncertainty associated with the estimation of rockmass properties has a significant impact on the design of underground excavations. Thus, a reliable estimate of the strength and deformation characteristics of rockmass is required for the stability analysis. Therefore, probabilistic analysis is adopted in this investigation using Rosenblueth's point-estimate method (RPEM).

2. FAILURE EVALUATION CRITERION

In order to assess the stability of the mine development intersection, a performance criterion must first be selected. This may be one of numerous conditions such as maximum permissible floor heave ratio or roof sag ratio, or allowable stress concentration factor (normally associated with linear elastic analyses), or a yielding condition such as Mohr-Coulomb or Hoek-Brown (Zhang and Mitri, 2008; Abdellah et al., 2012). The choice of a performance criterion is dependent on the application and field observations. In this current study, a yield-based criterion has been selected in which Mohr-Coulomb is used as the failure condition. The strength-to-stress ratio is a readily available parameter in FLAC3D (ITASCA, 2009) and a form of a safety factor. For mining applications, it is recognized that the factor of safety of permanent mine openings such as mine shaft and mine infrastructure should be higher than that used for mine developments, which are required to be opened and functional for the life of a mine (production) plan. Therefore, in this study, a strength-to-stress ratio of 1.4 was deemed an appropriate safety factor, given the fact that the required service life of the developments in the study area is only a few years.

Also, the unsatisfactory performance is determined when the extent of the strength-to-stress ratio contours, corresponding to Mohr-Coulomb strength-to-stress ratio <1.40 exceeds the anchorage limit of the rockbolt from the excavation surface. For a 2.40 m bolt, the minimum support limit from excavation surface is 2.10 m. Thus, the stability of mine development intersection becomes unsatisfactory if the following two conditions are met together:

- Mohr-Coulomb strength-to-stress ratio based yielding <1.40.
- Extent of the strength-to-stress ratio contours >2.10 m.

3. CASE STUDY

To examine the stability of mine development intersections, a plan view of the 1540 level is shown in Figure 2. The study zone is divided into the following three zones; hanging wall (HW), orebody, and footwall (FW). Haulage drifts, mine developments and their cross-cuts are driven into the footwall rockmass. The stope dimensions are 12×15×30 m (L×W×H). The stopes are extracted and then tight filled with a mixture of pastefill and waste rock.

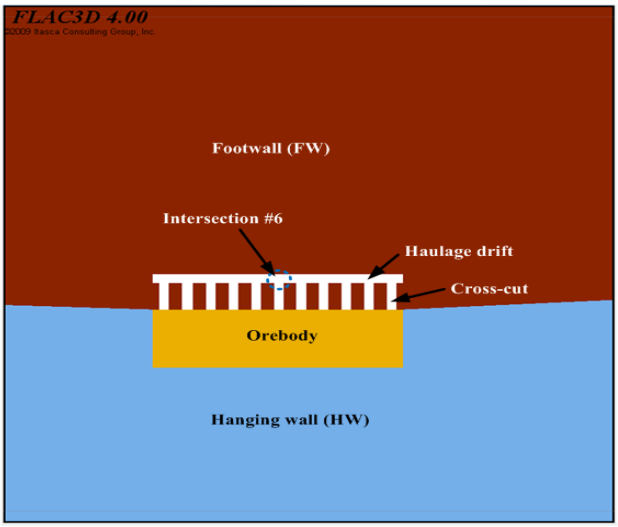


Figure 2: Level plan shows the mine development intersection#6 under the study.

The orebody has a strike length of approximately 220 m. To maintain better ground conditions, the stoping sequence from one level to another and along the ore strike should follow a pyramid shape as shown in Figure 3. Such sequence helps mitigate stress concentration and facilitate secondary stope mining thus increasing safety and mining recovery rate. The stability analysis is conducted for the orebody, whereby a planned sequence of 72 stopes

over six production levels (1600, 1570, 1540, 1510, 1480 and 1450) is simulated in the form of 18 mine-and-fill numerical model steps. While doing so, the strength-to-stress ratio is monitored on level 1540 at the intersection of the haulage drift with the cross cut #6 location.

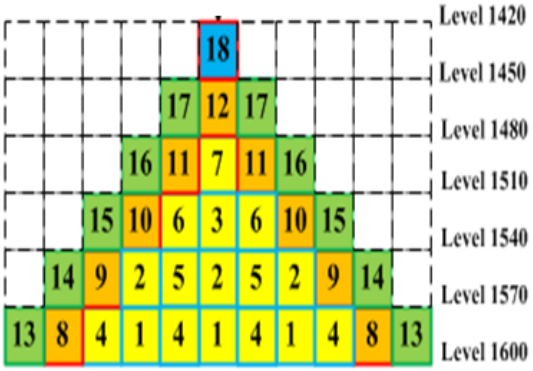


Figure 3: Pyramidal shape stoping sequence along the orebody strike.

4. NUMERICAL ANALYSIS

Rockmass properties are significant geotechnical design input parameters. These parameters are never known precisely. There are always uncertainties associated with them. Some of these uncertainties are due to lack of knowledge or limited collected data and some are intrinsic. Furthermore, some may arise from errors in testing (e.g. estimating strength of intact rocks, mapping the joint spacing, assessing the joint surface condition), and random data collection. All these uncertainties are attributed to the inherent nature of the rockmass characterization (Glaser and Doolin, 2000). Therefore, it is important to address the effect of these parameters on the design using probabilistic methods of analysis. Well assessment of uncertainty in rockmass characterization can assist to better understand how the decision of rock support design systems is affected by it.

In this investigation, the focus is the uncertainty arising from the rockmass properties (e.g. rockmass of footwall) and their effect on the stability of mine development intersections (e.g. which are driven in the footwall). Probabilistic methods provide a rational and efficient means of characterizing the inherent uncertainty that is common in geotechnical engineering. Because of the inherent uncertainty associated with parameters such as the rockmass properties around the openings, there is also uncertainty as to when and where additional rock support is required. Thus, predicting the probability of unsatisfactory performance using probabilistic analysis approaches together with the developed numerical modelling (deterministic techniques) becomes necessary.

4.1 Deterministic analysis

Deterministic analysis is performed to investigate the effect of mining sequence on the stability of the intersection #6 on level 1540. The physical and geomechanical properties of rockmasses used in the deterministic analysis are listed in Table 1 (Abdellah et al., 2013).

Table 1: Physical and geomechanical properties of rockmass properties used in the model (Abdellah et al., 2013).

Rock	Rockmass properties						
	C MPa	φ (^{0})	σ_t MPa	E GPa	υ	γ Kg/m^3	Ψ (^{0})
HW	5.1	52	0.53	45.5	0.24	2780	13.0
ORE	4.3	46.7	0.56	43.8	0.30	4530	11.68
FW	5.7	54.9	0.51	65.0	0.23	3170	13.73
BF	1	30	0.01	0.01	0.30	2000	7.50

The deterministic results show that the values of strength-to-stress ratio deteriorates as mining progresses in the roof, wall, pillar corner left, and pillar corner right. However, the two conditions of failure evaluation criterion are met in the roof after mining step 6 until the end of mining activity (e.g., from step 6 to step 18), whilst the conditions are not met in the wall of the intersection #6 during the whole mining steps. The two evaluation conditions are achieved in the pillar corner left after mining step 9 and in the pillar corner right after mining step 10. The complete deterministic analysis results of strength-to-stress ratio with respect to all 18 mining steps modelled are plotted in Figure 4. As can be seen, the wall the strength-to-stress ratio is well above the threshold of 1.4 thus suggesting satisfactory performance (e.g., the depth of the boundary limit is zero along all mining steps). For the roof at the intersection #6, the strength-to-stress ratio drops below the 1.4 limit after mining step 6. For the pillar corner left and pillar corner right, the ratio drops after mining steps 9 and 10, respectively.

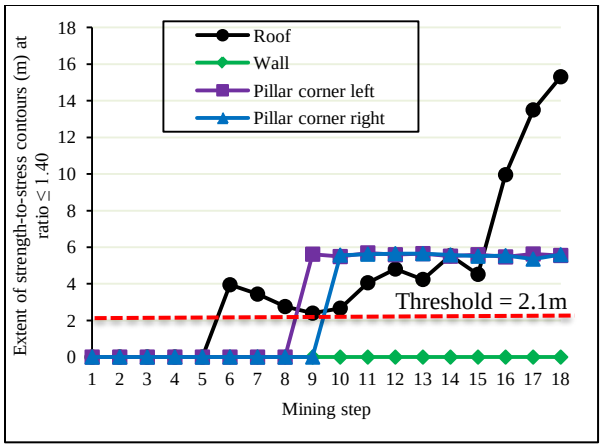


Figure 4: Extent of strength-to-stress contours at ratio of ≤ 1.4 at various mining step (deterministic analysis).

In light of these results, it can be said that secondary support may be recommended after mining step 6 in the roof (i.e. after 30 stopes have been extracted). For pillar corner left and pillar corner right, the secondary support may be recommended after mining step 9 (i.e., after 40 stopes have been extracted) and step 10 (i.e., after 44 stopes have been extracted), respectively. While these results are useful, the effect of the inherent uncertainty in rockmass properties is still unknown; hence the probabilistic analysis is necessary. This is presented in the following section.

4.2 Probabilistic analysis

Due to the heterogeneity of the rockmass, data from underground excavations are limited. Therefore, a great deal of uncertainty is inherent in the design of underground excavations. In order to develop a reliable design approach, one must use methods that incorporate the statistical variation of the numerical model input parameters representing the rockmass properties, i.e. mean, variance and standard deviation, as well as the design of rock failure criteria (Kwangho et al., 2005). Probabilistic material properties of the footwall are assigned (see Table 2). The means and standard deviations of these values are picked from the assumed normal distribution.

The sensitivity analysis can be carried out by varying a single parameter (random variable) at each run based on a specified coefficient of variation (COV) and monitoring the effect of this variation on the applied performance criterion. The variable at each run has one value of $(\mu - \sigma)$, or $(\mu + \sigma)$ while keeping all other parameters constant (no change in their average values). Sensitivity analysis gives a good understanding of the effect of certain parameters on the overall model behaviour. However, no distribution is obtained for the output parameters (random variables).

Based on the parametric study (sensitivity analyses) that has been conducted by Musunuri (Musunuri et al., 2009), the most influential model input parameters on the stability of mine haulage drift are Young Modulus (E), cohesion (C), and angle of internal friction (φ).

Table 2: Stochastic properties of footwall rockmass.

Rockmass property	Mean, μ	Standard deviation, σ	Coefficient of variance, δ
Cohesion (MPa)	5.70	1.14	0.20
Friction angle, (º)	54.90	10.98	0.20
Young's Modulus, (GPa)	65.0	13.0	0.20

4.2.1 Probabilistic results

The stochastic material properties of the footwall are assigned as listed in Table 2 above. The mean and standard deviations of these values are selected from a normal distribution. The Rosenblueth's (Rosenblueth, 1975) point-estimate method (RPEM) of 2^n (i.e., where n is number of stochastic input parameters) is adopted in this investigation for the above three input variables. The stochastic analysis results are plotted in Figure 5 for an average of 8 simulations (i.e., $2^3 = 8$).

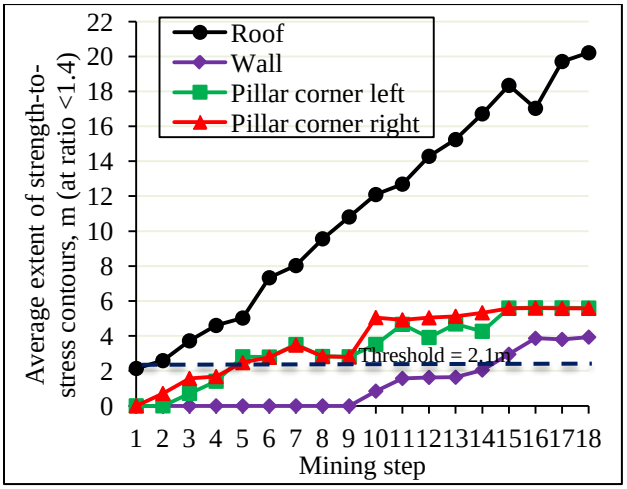


Figure 5: Average extent of strength-to-stress contours at ratio of ≤ 1.4 at various mining steps (stochastic analysis).

As depicted in Figure 5, the stochastic analysis agrees with the deterministic analysis in terms of showing that the strength-to-stress ratio deteriorates as mining progresses. In the roof of intersection #6 at 1540 level, the strength-to-stress ratio falls below threshold (i.e., ratio <1.4 and length >2.1 m) after mining step 1, versus step 6 with deterministic analysis. In the wall, the ratio does not fall below the

threshold in the deterministic analysis, whereas with stochastic analysis, it falls below threshold after mining step 15. For the pillar corner left, the performance criterion becomes unsatisfactory after mining step 5 with stochastic analysis where it deteriorates after mining step 9 with deterministic analysis. For pillar corner right, the failure also occurs after mining step 5 with stochastic analysis whereas its instability occurs after mining step 10 with deterministic analysis.

Comparing these two methods of analysis, stochastic results call earlier for secondary supports than with deterministic analysis (i.e., roof calls for secondary support after mining step 1 comparing with the deterministic analysis (after mining step 6)). Wall in deterministic analysis seems to be more stable and no support is required during the whole mining step comparing with probabilistic analysis (i.e., support may be required after mining step 15). Pillar corner left and right require support after mining step 5 with probabilistic analysis, compared with mining steps 9 and 10 with deterministic analysis. Thus, stochastic results appear to be more conservative than the deterministic analysis. The reason behind this is that the stochastic method takes into account the inherent uncertainty associated with input variables (i.e., rockmass properties). The deterministic analysis only uses the average values of rockmass properties as input parameters and gives only a single value as an output. However, the probability of unsatisfactory performance should be estimated to decide when and where secondary support is needed.

4.3 Probability of unsatisfactory performance

The probability of unsatisfactory performance is estimated for the roof, wall, pillar corner left and pillar corner right of intersection #6 at 1540 level, with respect to mining step. The suggested rating and ranking of likelihood of failure are given in Table 3. Standard normal distribution tables (Z-tables) are used to estimate the probability of failure, P*f*. The P*f* is obtained by subtracting the shaded area $\left(\text{shaded area}, Z^* = \left(\frac{\text{Threshold (X)} - \text{average value}(\mu)}{\text{standard deviation}\ (\sigma)}\right)\right)$; under the probability density function (PDF) curve from the unity which represents the total area $(P_f = 1 - Z^*)$. The results for the probability of unsatisfactory performance are plotted and categorized in Figure 6. As can be seen, the probability of unsatisfactory performance at the roof of the intersection #6 is certain after mining step 4 (i.e., P*f* >85%). Thus, the need for secondary support is necessary at this early stage (i.e., before step 4). On the other hand, the wall calls for secondary support at latest stages (i.e., after mining step 16) as the probability of unsatisfactory performance becomes likely (i.e., 60<P*f* <85%). The pillar corner right and left call for secondary support at middle stages (i. e., after steps 10 and 11, respectively) as the probability of instability becomes certain (i. e., P*f* >85%).

Table 3: Suggested rating and ranking of probability of unsatisfactory performance (Abdellah et al., 2012).

Rating	Ranking	Probability of Unsatisfactory Performance, P*f*	
1	Rare	< 5%	May occur in exceptional circumstances
2	Unlikely	5%-20%	Could occur at some time
3	Possible	20%-60%	Might occur at some time
4	Likely	60%-85%	Will probably occur in most circumstances
5	Certain	>85%	Expected to occur in most circumstances

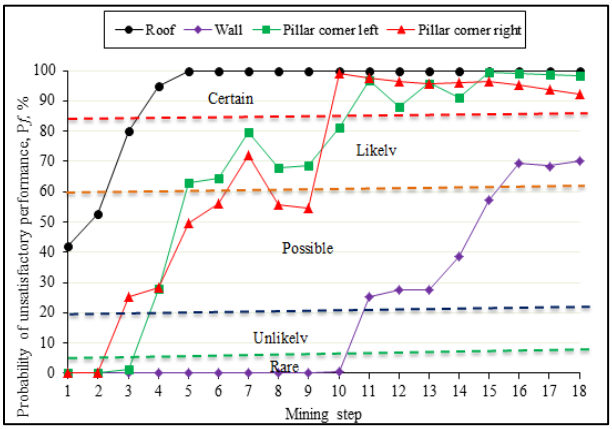


Figure 6: Probability of unsatisfactory performance at roof, wall, and pillar corner left and right of intersection #6 at level 1540 at various mining step.

5. CONCLUSION

Mine developments, such as haulage drifts, cross-cuts and their intersections, play a vital role in providing access to ore extraction areas for mine production. The stability of mine developments is thus of crucial importance during the life of a mine plan. This paper examines the stability of mine development access intersection #6 with respect to planned mining sequence. A 3D elastoplastic finite difference model is created using FLAC3D and employed in conjunction with the probabilistic method of analysis (RPEM) of 2^n, for a development intersection situated 1.5 km below the ground surface. The stability or performance of the

intersection is evaluated in terms of the strength-to-stress ratio. The stability performance of mine intersection is evaluated on the basis of the primary rock support length comprising 2.4 m resin grouted rebars in the roof and wall. The stability performance of the intersection is considered unsatisfactory if the strength-to-stress contours correspond to ratio <1.4 and extends beyond the anchorage limit of the rockbolt (i.e., >2.1 m).

The results are presented and categorized with respect to probability, instability, and mining stage. The probability of unsatisfactory performance, P*f*, of the intersection #6 is certain (P*f* >85%) in the roof after mining step 4, and is likely (i.e., 60<P*f* <85%) in the wall after mining step 16 (i.e., at the end of the mining step). The pillar corners right and left call for secondary support at the mid of mining step (i.e., steps 10 and 11, respectively) as the probability of instability is certain (i.e., P*f* >85%). Therefore, these results shed light on the requirement for the installation of enhanced support at the intersection during the planned mining step.

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