Haulage Drift Stability Analysis- A Sensitivity Approach

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**ABSTRACT** Haulage drifts are the primary access to the mining blocks of an ore body in a multi-level mining system of a tabular ore deposit. Drift instability could lead to serious consequences such as injuries, production delays and higher operational cost. Rockmass properties are significant geotechnical design input parameters. These parameters are never known precisely and always uncertainties associated with them.

The stability of the haulage drift is examined through parametric study of a nonlinear, elastoplastic, two-dimensional finite element model representing typical mining layout most commonly adopted in Canadian underground metal mines. The parametric study examines the influence of footwall rockmass geomechanical properties (e.g., cohesion, friction angle, dilation angle and Young’s Modulus) and the mining depth (e.g., horizontal-to-vertical stress ratio). Stability indicators are defined in terms of displacement, stress and the extent of yield zones, which adopt as a basis for assessing the effect of different parameter on the stability of haulage drift.

**Keywords:** Stability, haulage drift, rockmass properties

1 INTRODUCTION

Drifts are the arteries of mines, e.g. they are used to transport the blasted ore (valuable minerals) out of mining zone. Drift instability causes ground caving, thus can be a serious problem e.g. injuries, production delay and increase in operation costs. As the mine haulage drifts are the only access where loaders and/or trucks travel through, they must remain stable during their service life (Abdellah et al., 2013 and 2014, Wei et al., 2012, Zhang and Mitri, 2008).

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, limited collected data, errors in testing and random data collection. Therefore, a one should use a tool, such as sensitivity analysis to tackle these inherent uncertainties associated with the rockmass properties.

1.1 Problem Definition

To evaluate the stability of mine haulage drift, A two-dimensional, elastoplastic, finite element model (Phase 2D) is created as shown in Figure 1. The study zone is divided into three zones; hanging wall, orebody and footwall. The orebody consists of massive sulphide rock (MASU). The hanging wall contains Metasediments (MTSD) and the footwall comprises of Norite rock (NR). Three stopes are modelled to simulate the ore extraction with respect to mining step. The haulage drift is driven in the footwall and its dimensions are 4.5 m by 4.5 m and at a distance of 15 m from the nearest orebody (e.g., stope 3).

The physical and geomechanical properties for the different rockmass units included in this study are presented in Table 1 (Abdellah et al., 2012).
1.2 Dealing with Uncertainty

As mentioned before, 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).

To quantify the uncertainty related to the model input parameters, three possible ways exist: deterministic analysis, sensitivity analysis, and simulation approach. This paper focuses on the parametric (sensitivity) analysis which will be discussed in the next section.

2 SENSITIVITY ANALYSIS

Numerical models are known to be deterministic by nature, i.e. a set of model input parameters will produce a unique set of results in terms of stress, deformation, and yield pattern. It is for this reason, model parametric study adopting sensitivity analyses is often carried out to allow for the better understanding of the problem, e.g. stability of mine openings, as a result of changing in some of critical model input parameters (e.g. Cohesion, Young’s modulus, angle of internal friction, horizontal-to-vertical stress ratio) (Musunuri et al., 2009).

In a sensitivity analysis, a single parameter is systematically varied while all the other parameters are kept constant. The sensitivity analysis provides an understanding of the effect of each parameter on the overall behavior of the model. However, no distribution is obtained for the output parameters (random variables). It can be carried out by varying single parameter (random variable), at each run, based on 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 \([\mu-\sigma], \mu\) and \([\mu+\sigma]\) while keeping all other parameters is constant (no change in their average values).

Five footwall rockmass parameters namely: cohesion, friction angle, dilation angle, Young’s Modulus and horizontal-to-vertical stress ratio are varied to evaluate their effects on the stability of haulage drift with respect to mining step, as listed in Table 2.
3 DRIFT STABILITY EVALUATION CRITERION

In the following section, three evaluation criteria are described, which are used as a basis for the interpretation of numerical model results for the assessment of the stability of the mine haulage drift with respect to mining step.

3.1 Extent Of Yield Zone

Yielding is the most common criterion used in numerical modelling when elastoplastic model is employed. This condition occurs when the stress state reaches the surface of the yield function, which is when the rock is loaded beyond its elastic limit. In this study, Mohr-Coulomb yield function is adopted as a measure for “drift satisfactory or /and unsatisfactory performance”.

3.2 Displacement/Convergence Criteria

Displacement/convergence criteria depend on the stiffness of the rockmass properties and the purpose of underground opening. In the following, three displacement-based criteria are introduced.

3.2.1 Wall convergence ratio (WCR)

WCR is defined as the ratio of the total magnitude of the wall closure to the span of the initial drift as shown in Equation (1):

\[ WCR = \left( \frac{W_0 - W_d}{W_0} \right) \times 100 \]  

Where: \( W_0 \) is the original span of the drift and \( W_d \) is the span of the drift after deformation.

3.2.2 Roof sag ratio (RSR)

RSR is defined as the ratio of the roof sag (\( \Delta S \)) to the span of the drift as given in Equation (2):

\[ RSR = \left( \frac{\Delta S}{W_0} \right) \times 100 \]  

3.2.3 Floor heave ratio (FHR)

FHR is defined as the ratio of the floor heave (\( \Delta h \)) to the span of the drift, Equation (3):

\[ FHR = \left( \frac{\Delta h}{W_0} \right) \times 100 \]  

3.3 Mining-Induced Major Principal Stress (\( \sigma_1 \))

It defines the location of high stresses areas due to mining activity.

4 RESULT AND DISCUSSION

In the following section, the effect of each varied parameter will be demonstrated to show its effect on the stability of mine haulage drift based on the previous stability indicators.

Table 2. Footwall model input parameters at each run

<table>
<thead>
<tr>
<th>Run / parameter</th>
<th>k, MPa</th>
<th>C, GPa</th>
<th>E, GPa</th>
<th>( \phi ), degree</th>
<th>( \psi ), degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>1.65</td>
<td>11.2</td>
<td>24</td>
<td>35</td>
<td>7.5</td>
</tr>
<tr>
<td>Run 2</td>
<td>1.98</td>
<td>11.2</td>
<td>24</td>
<td>35</td>
<td>7.5</td>
</tr>
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<td>1.32</td>
<td>11.2</td>
<td>24</td>
<td>35</td>
<td>7.5</td>
</tr>
<tr>
<td>Run 4</td>
<td>1.65</td>
<td>13.44</td>
<td>24</td>
<td>35</td>
<td>7.5</td>
</tr>
<tr>
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<td>1.65</td>
<td>8.96</td>
<td>24</td>
<td>35</td>
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<tr>
<td>Run 6</td>
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<td>11.2</td>
<td>28.8</td>
<td>35</td>
<td>7.5</td>
</tr>
<tr>
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<td>1.65</td>
<td>11.2</td>
<td>20.8</td>
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<td>7.5</td>
</tr>
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<td>24</td>
<td>42</td>
<td>7.5</td>
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<td>28</td>
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<td>24</td>
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<td>10.5</td>
</tr>
<tr>
<td>Run 11</td>
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<td>11.2</td>
<td>24</td>
<td>35</td>
<td>7.5</td>
</tr>
</tbody>
</table>
4.1 Effect Of The Horizontal-To-Vertical Stress Ratio “K” On The Evaluation Criteria

The ratio, k, is defined as the average horizontal stress $\sigma_h$ to the vertical stress $\sigma_v$ as given in Equation (4):

$$K = \frac{\sigma_h}{\sigma_v} \quad (4)$$

The effect of “K” on the stability indicators is discussed below.

4.1.1 Effect of “K” on the stress

In the Canadian Shield, k varies nonlinearly with the depth. At shallow depth, k tends to be larger than it is in deeper mines. As shown in Figure 2, the increase of “K” (e.g., increase horizontal stress due to increase in depth) results in increase of major induced-mining principal stress at drift roof and floor. On the other hand decrease in the major induced-mining stress at the drift walls.

Figure 2. K- value versus Major induced-mining principal stress.

4.1.2 Effect of “K” on the displacement

Displacement convergence criteria are generally site specific; they depend not only on the rock mass stiffness characteristics but also on the intended use of the underground opening as well as the design and code requirements. As illustrated in Figure 3, the increase of “K” value results in increase in the displacement/convergence criteria around mine haulage drift. The more effect occurs in the roof of the drift (e.g., shown by increase of the roof sag ratio “RSR”) followed by right wall of the drift. The less effect appears in the drift left wall.

Figure 3. K- value versus displacement/convergence criteria.

4.1.3 Effect of “K” on the extent of yielding zones

Yielding criterion is widely used in numerical modeling when elastoplastic model is adopted. Thus yielding may be considered as an important factor contributing to instability. As shown in Figure 4 below, the extent of yield zones increases as “K” increases. It can also be seen that the yielding zone extends around haulage drift as mining progresses. The maximum length of the yielding zone exceeds 15m in the left sidewall (LW) of haulage drift.

Figure 4. K- value versus extent of yielding zones.

The development of yield zones with modelling mining steps based on Mohr-Coulomb criterion and average “K-value” of 1.65 is shown in Figure 5(a-d). It is obvious that the yielding zones increases as mining advances.
4.2 Effect Of Cohesion

Cohesion is a measure of internal bonding of the rock material. For example, if a shear force is applied to a cube of muddy soil or rock at zero normal pressure, the resulting shear deformation is accompanied by a measurable resistance. The resistance force per unit area is termed cohesion.

4.2.1 Effect of cohesion on the stress

In natural soils, cohesion results from electrostatic bonds between clay and silt particles. Thus, soils devoid of clay or silt are not cohesive except for capillary forces arising when little water forms bridges between sand grains, resulting in negative pore pressure (suction). In contrast, rocks normally exhibit much greater cohesion, thousands of times larger than soils. Figure 6 generally depicts that, as cohesion of rockmass increases the major induced-mining stress decreases. The most decrease occurs in the sidewalls of the haulage drift (e.g., left wall (LW) and right wall (RW)).

4.2.2 Effect of cohesion on the displacement/convergence criteria

Increase of cohesion results in decrease in the displacement (e.g., deformation) as shown in Figure 7.

4.2.3 Effect of cohesion on the extent of yielding zone

Figure 8 shows that, as cohesion increases, the yielding zones decreases.

Figure 5. Development of yield zones with modelling mining steps at average “K-value” of 1.65.

Figure 6. Cohesion versus major induced-mining principal stress

Figure 7. Cohesion versus displacement/convergence criteria.

Figure 8. Extents of yield zones around haulage drift at two different cohesion values (final mining step).
As shown in Figure 9 above, the increase in cohesion results in reduction in the extent of yielding or failure zones.

### 4.3 Effect of Young’s Modulus

Young's Modulus is modulus of elasticity measuring of the stiffness of a rock material. It is defined as the ratio, for small strains, of the rate of change of stress with strain. This can be experimentally determined from the slope of a stress-strain curve obtained during compression or tensile tests conducted on a rock sample. Similar to strength, Young’s Modulus of rock materials varies widely with rock type. For extremely hard and strong rocks, Young’s Modulus can be as high as 100 GPa. There is some correlation between compressive strength and Young’s Modulus.

#### 4.3.1 Effect of stiffness on the stress

The increase of Young’s Modulus (E) means increase the stiffness of the rockmass. The induced-mining principal stress decreases as stiffness increases, as shown in Figure 10. It can be seen that, the biggest drop in the major induced mining stress occurs in the drift left wall (LW), while the smallest decrease occurs in the drift back (roof).

#### 4.3.2 Effect of stiffness on the displacement/convergence criteria

Figure 11 shows that, as stiffness (e.g., Young’s Modulus) increases the displacement/convergence of haulage drift due to mining activity reduces. Thus means more stable condition.

#### 4.3.3 Effect of stiffness on the extent of yielding zones

Figures 12 and 13 illustrate the decrease of the yielding zone extension as stiffness increases. The maximum decrease in the extension of yielding zones happens in the drift sidewalls.
4.4 Effect of Friction Angle

4.4.1 Effect of friction angle on the stress

As depicted in Figure 14 below, the increase of friction angle of rockmass results in the decrease of major induced-mining principal stress except for the floor of the drift.

4.4.2 Effect of friction angle on the displacement/convergence criteria

Figure 15 shows that, displacement/convergence decreases as friction angle increases.

4.4.3 Effect of friction angle on the extent of yielding zones

As shown in Figures 16 and 17, increase of friction angle produces decrease in the extent of yielding zones around haulage drift.
4.5 Effect Of Dilation Angle

Dilation angle is one of the parameters that are not easily obtained for elastoplastic simulation of rock materials. The following section presents discussion of the sensitivity of results to the dilation angle and how this may affect the stability of haulage drift in terms of stress distribution pattern, displacements in the rockmass, and extent of yield zone.

4.5.1 Effect of dilation angle on the stress

The dilation angle has practically no effect on the stress distribution pattern and overall magnitude at locations sufficiently far from the drift, i.e. outside the stress relaxation zone. But, it affects the final magnitude of the principal stress inside the stress relaxation zone. Figure 18 illustrates that, major induced-mining principal stress decreases with the increase of dilation angle.

![Figure 18. Dilation angle versus major induced-mining principal stress](image)

4.5.2 Effect of dilation angle on the displacement/convergence criteria

The dilation angle is directly increases when friction angle increases (e.g., dilation angle equals one-fourth friction angle ($\Psi = \phi/4$). Thus produces the same effect on the displacement/convergence as the friction angle. Figure 19 shows the effect of dilation angle on the displacement/convergence criteria. As shown, the increase of dilation angle produces decrease in displacement.

![Figure 19. Dilation angle versus displacement/convergence criteria.](image)

4.5.3 Effect of dilation angle on the extent of yielding zones

Dilation angle affects the final yield zones inside the stress relaxation zone. As the dilation increases, the final yield zone decreases. Figure 20 shows the decrease of the length of yielding zones as dilation angle increases.

![Figure 20. Dilation angle versus extent of yielding zones](image)

5 CONCLUSION

This paper presents a sensitivity analysis to evaluate the stability of a mine haulage drift due to the heterogeneity associated with rockmass geotechnical input parameters. In this method, a single parameter is systematically varied, based on coefficient of variation, while all the other parameters are kept constant. Thus provides better understanding of the effect of each parameter on the overall behavior of the model. The stability of the haulage drift is examined through parametric study of a
nonlinear, elastoplastic, two-dimensional finite element model representing typical mining layout most commonly adopted in Canadian underground metal mines. Stability indicators are defined in terms of displacement, stress and the extent of yield zones, which adopt as a basis for assessing the effect of different parameter on the stability of the haulage drift. Five parameters have been used in this study to check their effect on the stability of haulage drift are: horizontal-to-vertical stress ratio (K), cohesion (C), Young’s modulus (E), friction angle and dilation angle ($\psi$).

6 RECOMMENDATIONS

There are other parameters are not included in this study, e.g. mining depth, distance between haulage drift and stopes and mining sequences. Three-dimensional modelling is required to simulate the real geometry of the case study. Once the model is constructed, in-situ stress measurements should be used to calibrate the numerical model. Rock failure criteria such as Mohr-Coulomb must be calibrated based on underground measurements such as deformations (Multi-Point Borehole Extensometer or MPBX) and rockbolt loads. Although sensitivity gives good understanding of the effect of certain parameter on the overall behaviour of the model, there is not distribution or probability of failure obtained. Therefore, probabilistic analysis should be invoked to study the probability of unsatisfactory performance of the haulage drift.

REFERENCES


