A CASE STUDY OF RISK EVALUATION AT CERREJON MINE
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ABSTRACT

A risk study was carried out at the Cerrejon coal mine in order to assess the impacts of pit slope failure in terms of safety of personnel and destruction of equipment with economic consequences. Results of the assessment enabled the definition of risk treatment requirements and the identification of key aspects to consider in a risk treatment plan.

The approach included the following tasks:

(1) **Assessment of the total probability of failure (POF) representative of the stability conditions of typical footwall and highwall slopes.** For this purpose, stability analyses were carried out to define the Design POF, which accounts for the variability of strength parameters and represents the normal conditions considered for slope design. Strength parameters for highwall slope analysis were derived from borehole data obtained with a geotechnical drilling campaign. The Total POF was estimated through the use of Source Response Diagrams (SRD) in order to incorporate other sources of uncertainty not accounted for, like changes in geometry, variability of rock conditions due to geological or operational factors, changes in groundwater conditions and occurrence of seismic events.

(2) **Assessment of the consequences of footwall and highwall slope failure on safety of personnel.** The assessment was performed through the use of event tree analysis to establish the probability of fatality caused by slope failures, from the Total POF defined in the previous task. This analysis required the evaluation of personal exposure to slope failures. Also, the assessment included benchmarking of acceptability criteria in terms of probability of fatality and the evaluation of options of risk mitigation to comply with these criteria.

(3) **Assessment of the consequences of footwall and highwall slope failure in terms of economic losses associated with impact on equipment.** The analysis included the evaluation of equipment exposure to slope failures, and it was performed through event tree analysis to establish the probability of an economic loss associated to total or partial lost of equipment, from the total POF value defined in the first task. The magnitude of the economic losses was estimated from the costs of damaged equipment, lost production and site restoration. Options of risk mitigation were also examined in terms of economic losses.
The risk assessment process applied to the Cerrejón mine showed how the system can be applied to evaluate the consequences of failure in terms of personnel safety and economics and to identify the more adequate risk mitigation options. The system can be an extremely powerful tool in the mine design process and provides the opportunity to rationalize the geotechnical information requirements, once the risk criteria have been defined by management.

The main purpose of this paper is to present the process; therefore, the emphasis has been put on the methodology followed rather than on the actual results obtained.

1. INTRODUCTION

The study described in this paper corresponds to the work carried out by SRK Consulting for Carbones del Cerrejón during the final quarters of years 2003 and 2004, intended to assess the risks of pit slope failures.

The Cerrejón coal mine is located in the Guajira province, in the northern part of Colombia, over an area of approximately 50 km long by 15 Km wide as indicated in Figure 1. The planned mine object of this study will be developed over 14 different areas, with open pits excavated along the strike of target coal seams. The final pits will consist of box cuts defined by footwall, highwall and endwall slopes, with typical final heights of 240 m. For the purpose of this study, the pit geometry was idealized as will be described in Section 4.2.
The main objectives of the study were:

- To assess the impacts of slope failure in terms of safety and economic consequences for both footwall and highwall slopes.
- To define the need for risk treatment by benchmarking the calculated impacts and comparing with acceptability criteria.
- To identify the key aspects to consider in a risk treatment plan.

The methodology included the following main tasks:

- Evaluation of the total probability of failure of typical footwall and highwall slopes. Probability diagrams (Source Response Diagrams) were used for this purpose in order to account for uncertainties not included in the slope stability model used for design.
- Assessment of risk associated to safety of personnel that might be impacted by the occurrence of slope failures. Event tree diagrams were used for this purpose, which together with the results of the exposure analysis, enabled the estimation of probabilities of fatality. Benchmark criteria were used to define acceptable risk levels.
- Assessment of risk associated to economic losses derived from equipment being impacted by the occurrence of slope failures. Event tree diagrams were used for this purpose, which utilizing the results of the exposure analysis, enabled the estimation of probabilities of economic losses and the magnitude of these losses.

2. APPROACH

A Probability of Failure (POF) philosophy is being used at Cerrejón for pit design. This method is seen as a more meaningful approach than the conventional Factor of Safety (FOS) approach, which inherently varies depending on the reliability of the underlying database. However, both of these methodologies have difficulty in defining the best acceptability criteria such that an optimum benefit can be obtained with an acceptable risk associated with slope failure. The risk consequence approach intends to solve this drawback.

There are many methods available for developing a risk consequence process. However, they all contain some common steps. These are:

1. Identify the event generating hazards;
2. Assess the likelihood or probability of occurrence of these events;
3. Assess the impact of the hazard;
4. Combine the probability and impact to produce an assessment of risk;
5. Compare the calculated risk with benchmark criteria to produce an assessment of risk, and
6. Use the assessment of risk as an aid to decision making.
The work described in the present paper refers mainly to the steps 2 to 5 of this methodology, applied to the risk assessment of the pit slopes for the Cerrejón mine. The flow chart presented in Figure 2 (adapted from Reference 1) illustrates the pit slope risk assessment process.

The risks associated with a major slope failure can be categorized by the following consequences:

- Injury to personnel;
- Damage to equipment;
- Economic impact on production;
- Force Majeure (a major economic impact);
- Industrial action;
- Public relations, such as stakeholder resistance, environmental impact etc.

Three of the six consequences are all economically related, although on different scales. These differentiated scales equate to the acceptable risk (or the risk criterion) that would apply to each case. Each of the risks quantified must be acceptable to the mine owners, and are related to the probability of failure of the slopes evaluated through the risk assessment methodology.

The diagram presented in Figure 3 illustrates the methodology used for the risk consequence analysis of pit slopes. The scope defined for the study included only the first three consequences.
In particular the study consisted of the following tasks:

- Assessment of the total probability of failure (POF) representative of the stability conditions of typical footwall and highwall slopes.
- Assessment of the consequences of footwall and highwall slope failure on safety of personnel.
- Assessment of the consequences of footwall and highwall slope failure in terms of economic losses associated with impact on equipment.

In the following sections these tasks will be described in detail.

3. PROBABILITY OF SLOPE FAILURE

3.1 Objective

The objective of this task was the assessment of the likelihood of occurrence of slope failure events that might have impacts on personnel and equipment. This was done through the estimation of the total probability of failure (Total POF) representative of the stability conditions of typical footwall and highwall slopes.

3.2 Probability of Failure (POF) of Slopes – Normal Conditions

The probability of failure (POF) of footwall and highwall slopes was available from previous studies (References 2, 3 and 4) that intended to define design conditions for the pits. For those analyses a probabilistic approach was used, enabling the calculation of probabilities of failure associated with variability of strength parameters and representing...
in general the normal conditions considered for slope design. Some additional specific analyses were carried out for the present study in order to incorporate new information available.

3.2.1 POF of Footwall Slope

Conditions of Analysis:

For the footwall slopes, conditions of analysis representing the typical slope bench under normal conditions (Figure 4) were:

- straight slope parallel to the bedding,
- bedding angle of 20º, consistent with the geological model,
- slope height of 60 m (back calculated value for a rounded POF),
- ubiquitous weak seams so that critical slip surfaces were searched for with the model,
- ground water position at mid-height defining a half saturated slope,
- distribution of ground water pressures represented by \( Ru \) values of 0.2 (dewatered slope),
- toe strength represented by \( c = 180 \text{ KPa} \pm 30 \text{ KPa} \) and \( \phi = 18^\circ \pm 3^\circ \) and
- bedding strength (weak) represented by \( c = 38 \text{ KPa} \pm 16 \text{ KPa} \) and \( \phi = 16^\circ \pm 4^\circ \)

![FIGURE 4 – Footwall Slope Bench – Normal Conditions](image)

Estimation of Strength Parameters:

Toe strength parameters were defined from back analysis of slope failures. Bedding strength parameters were defined from results of a direct shear tests campaign completed in 1999 with samples from the Cerrejon Central area. Justification of these parameters is presented in Reference 2.

Results of the Analysis:

The slope stability evaluation resulted in the selection of a Design POF of 5% for individual benches at the footwall slopes. Because the stepped slopes considered ample
bench widths corresponding to 35 m thick rock beds, benches behave independently from each other in terms of stability conditions. For this reason, footwall bench failure was considered the subject of the risk assessment in terms of impacts on personnel and equipment.

3.2.2 POF of Highwall Slope

Conditions of Analysis:

For the highwall slopes, conditions of analysis representing the typical inter ramp slope under normal conditions (Figure 5) were:

- inter-ramp slope conformed by three, 10 m high by 5 m wide, benches,
- inter-ramp slope angle of 63°,
- inter-ramp slope height of 30 m,
- dip of bedding favorable to stability,
- ground water position at mid-height defining a half saturated slope,
- distribution of ground water pressures represented by Ru values of 0.2 (dewatered slope), and
- rock mass strength represented by c = 356 KPa ±164 KPa and φ = 39.6° ±6.6°

![FIGURE 5 – Inter Ramp Highwall Slope – Normal Conditions](image)

Estimation of Strength Parameters:

Rock mass strength parameters for highwall slope analysis were defined from 15 borehole logs obtained in the geotechnical drilling campaign of 2003. Boreholes close to highwall slope locations were selected for this analysis. The logs were processed to estimate values of the Geological Strength Index (GSI) and the Uniaxial Compressive Strength (UCS), representing rock characteristics of each core run. These information together with the logging data were used to calculate the Mohr-Coulomb strength parameters c and phi, applying the Hoek and Brown strength criterion as described in Reference 5. A disturbance factor D of 0.7 and a stress level consistent with the situation
of the 30 m high inter ramp slopes, were assumed to represent average conditions for the highwall slopes. More than 3000 sets of values were generated, which then were reduced by weighted averaging to 108 sets representing conditions of 30 m thick rock packages, consistent with the scale of the inter ramp slopes. Figure 6 shows a graph of c versus phi with the results of this analysis.

In a similar manner, strength parameters representing two particular abnormal conditions were estimated, which were then used for the estimation of the total probability of failure of the slope as described in the following Section. These conditions included reduced rock mass strength due to geological features and reduced rock mass strength due to disturbance caused for poor blasting.

For the first case, 40% of the data points representing the poorer rock mass conditions crossed with the boreholes were used to calculate the reduced strength parameters representative of adverse geological conditions. Results of this analysis indicated that the reduced strength conditions due to geological factors could be represented by $c = 199$ KPa $\pm 56$ KPa and $\phi = 33.5^\circ \pm 5.3^\circ$.

Disturbed rock mass conditions due to poor blasting were considered by assuming a disturbance factor $D$ of 1.0 for the estimation of the strength parameters, using all the 106 data sets. Results of this analysis indicated that the reduced strength conditions due to poor blasting could be represented by $c = 287$ KPa $\pm 140$ KPa and $\phi = 35.1^\circ \pm 7.1^\circ$. 

**FIGURE 6 – Rock Mass Strength Parameters for Highwall Slope Stability**
Results of the Analysis:

The probabilistic analyses were performed with the program SLIDE from Rocscience, through a Monte Carlo simulation of the strength variability. A log normal distribution for the Mohr-Coulomb parameters was assumed and the correlation between c and phi defined from data analysis was accounted for in the Monte Carlo analysis. Results of the stability analysis for normal conditions indicated a Design POF of 0.28% for the inter-ramp slopes. Inter-ramp slope failure is the subject of the risk assessment in terms of impacts on personnel and equipment.

3.3 Total Probability of Failure (Total POF) of Slopes

The Total POF was estimated through the use of Source Response Diagrams (SRD), which enable the incorporation of other sources of uncertainty not accounted for in the design of the slopes, like changes in geometry, variability of rock conditions due to geological or operational factors, changes in groundwater conditions and occurrence of seismic events. These factors represent abnormal deviations from the normal conditions assumed for the design of the slopes. Figure 7 shows a typical SRD, corresponding to the case of geology deviation in a highwall slope.

![FIGURE 7 – SRD for Geology Deviation in Highwall Slope](image)

The assumed conditions representing the departure from normal conditions were evaluated with the slope stability model to calculate the effect of these situations on the POF of the slope. For this purpose, slope stability analyses with the program SLIDE,
were carried out to quantify changes in POF values. Both favorable and unfavorable variations of the aspect under analysis were considered, and for each case, the possible responses during operation were evaluated in terms of their probability of occurrence. Therefore, the diagram enabled the consideration of both, threats to and opportunities for the stability condition of the slope. In this way, the net contributions to the Total POF resulting from the assumed variations for each aspect were evaluated.

Tables 1 and 2 present, for footwall and highwall slopes, respectively; the summaries of input parameters and results of analysis, of the 10 cases considered to evaluate the effect of occurrence of abnormal conditions. These analyses include situations related to variations in slope geometry, geology, blasting effects, water conditions and seismic events. The case no. 1 in these Tables corresponds to the Design situation or normal conditions and is the reference value that enables the calculation of the net contributions to the Total POF with the SRD diagrams.

Total POF values of 7.3% and 0.5% were defined for footwall and highwall slopes, respectively. These results indicate that the uncertainties not accounted for in design added 2.3% and 0.25% to the Design POF (normal conditions) of these slopes, respectively.

Figures 8 and 9 show the complete SRD’s for the evaluation of the Total POF of footwall and highwall slopes, respectively.

Contributing factors to the Total POF considered are: bedding geometry deviation, abnormal rock mass quality deviation due to geology, abnormal rock mass quality deviation due to mine operation, deviation in water conditions and occurrence of seismic events.

Table 1 – Results of Stability Analysis of Footwall Slopes

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Variation Aspect</th>
<th>Slope Angle (º)</th>
<th>Water Conditions</th>
<th>Toe Strength</th>
<th>Loading Cond.</th>
<th>POF (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Base case. CoC = 0</td>
</tr>
<tr>
<td>1</td>
<td>normal</td>
<td>20</td>
<td>half</td>
<td>0.2</td>
<td>180 30 18.0 3.0</td>
<td>static</td>
<td>5.06</td>
</tr>
<tr>
<td>2</td>
<td>geometry</td>
<td>15</td>
<td>half</td>
<td>0.2</td>
<td>180 30 18.0 3.0</td>
<td>static</td>
<td>0.63</td>
</tr>
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<td>3</td>
<td>geometry</td>
<td>25</td>
<td>half</td>
<td>0.2</td>
<td>180 30 18.0 3.0</td>
<td>static</td>
<td>25.66</td>
</tr>
<tr>
<td>4</td>
<td>geology</td>
<td>20</td>
<td>half</td>
<td>0.2</td>
<td>150 30 15.0 3.0</td>
<td>static</td>
<td>9.67</td>
</tr>
<tr>
<td>5</td>
<td>geology</td>
<td>20</td>
<td>half</td>
<td>0.2</td>
<td>210 30 21.0 3.0</td>
<td>static</td>
<td>2.76</td>
</tr>
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<td>6</td>
<td>blasting</td>
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<td>half</td>
<td>0.2</td>
<td>165 30 16.5 3.0</td>
<td>static</td>
<td>7.35</td>
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<tr>
<td>7</td>
<td>blasting</td>
<td>20</td>
<td>half</td>
<td>0.2</td>
<td>195 30 19.5 3.0</td>
<td>static</td>
<td>3.61</td>
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<tr>
<td>8</td>
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<td>full</td>
<td>0.40</td>
<td>180 30 18.0 3.0</td>
<td>static</td>
<td>31.21</td>
</tr>
<tr>
<td>9</td>
<td>water</td>
<td>20</td>
<td>none</td>
<td>0</td>
<td>180 30 18.0 3.0</td>
<td>static</td>
<td>1.96</td>
</tr>
<tr>
<td>10</td>
<td>seismic</td>
<td>20</td>
<td>half</td>
<td>0.2</td>
<td>180 30 18.0 3.0</td>
<td>0.12g</td>
<td>63.96</td>
</tr>
</tbody>
</table>

Unit weight : 2.5 Ton/m2  Bedding Strength: c 38 KPa ± 16 KPa
Slope Height : 61 m φ 16° ± 4°
Table 2 – Results of Stability Analysis of Highwall Slopes

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Variation Aspect</th>
<th>Slope Angle (º)</th>
<th>Water Cond.</th>
<th>Ru</th>
<th>c (KPa)</th>
<th>SD c</th>
<th>phi (º)</th>
<th>SD phi</th>
<th>Loading Cond.</th>
<th>POF (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>normal</td>
<td>63</td>
<td>half 0.2</td>
<td>356</td>
<td>164</td>
<td>39.6</td>
<td>6.6</td>
<td>Base case. CC = 0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>geometry</td>
<td>56</td>
<td>half 0.2</td>
<td>356</td>
<td>164</td>
<td>39.6</td>
<td>6.6</td>
<td>Flatter slope (5 degrees)</td>
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<td></td>
</tr>
<tr>
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<td>geometry</td>
<td>70</td>
<td>half 0.2</td>
<td>356</td>
<td>164</td>
<td>39.6</td>
<td>6.6</td>
<td>Steeper slope (5 degrees)</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>geology</td>
<td>63</td>
<td>half 0.2</td>
<td>356</td>
<td>164</td>
<td>39.6</td>
<td>6.6</td>
<td>Dip of fracture at toe 10º</td>
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<td></td>
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<tr>
<td>5</td>
<td>geology</td>
<td>63</td>
<td>half 0.2</td>
<td>356</td>
<td>164</td>
<td>39.6</td>
<td>6.6</td>
<td>Clinker, faults. CC = 0.83</td>
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<td>6</td>
<td>blasting</td>
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<td>half 0.2</td>
<td>287</td>
<td>140</td>
<td>35.1</td>
<td>7.1</td>
<td>Rock damage. CC = 0.88</td>
<td></td>
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</tr>
<tr>
<td>7</td>
<td>blasting</td>
<td>63</td>
<td>half 0.2</td>
<td>391</td>
<td>137</td>
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<td>Reinforced slope</td>
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<td>8</td>
<td>water</td>
<td>63</td>
<td>full 0.4</td>
<td>356</td>
<td>164</td>
<td>39.6</td>
<td>6.6</td>
<td>Full slope wet, Ru = 0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>water</td>
<td>63</td>
<td>none 0</td>
<td>356</td>
<td>164</td>
<td>39.6</td>
<td>6.6</td>
<td>Dry slope</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>10</td>
<td>seismic</td>
<td>63</td>
<td>half 0.2</td>
<td>356</td>
<td>164</td>
<td>39.6</td>
<td>6.6</td>
<td>Seismic loading</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Unit weight : 2.5 Ton/m2
Slope Height : 30 m
Fracture Strength: c 38 KPa ± 16 KPa (Case No. 4) 16º ± 4º
FIGURE 8 – Evaluation of Total POF of Footwall Slopes
FIGURE 9 – Evaluation of Total POF of Highwall Slopes
4. RISK ANALYSIS OF SLOPE FAILURE – SAFETY IMPACT

4.1 Objective

The objective of this task was the assessment of the consequences of footwall and highwall slope failure on safety of personnel. This is done through the estimation of the probability of fatality caused by slope failures, the comparison of this result with acceptability criteria and evaluation of options of risk mitigation.

4.2 Exposure Analysis of Personnel

The purpose of the exposure analysis is to estimate the probability of coincidence in time and space of mine personnel with an eventual slope failure. The analysis requires the definition of a typical pit layout which in turn defines the equipment modules and personnel required to achieve the defined annual production. Exposure factors are then estimated, for fixed equipment and for trucks, using simple relationships derived from the geometry of the idealized pit and from statistical data on the actual performance of equipment. Exposure of personnel is established from that of equipment, as equipment operators made the greatest proportion of people exposed to slope failures.

A total mine production of 30 million tons of coal per year and 7 pit areas were assumed. The typical pit layout considered is indicated in Figure 10. It has a depth of 240 m, a footwall slope with four, 60 m wide benches and an overall angle of 16°, a highwall slope with seven, 38 m wide ramps used by trucks to transport waste and coal. Both backfill and ex-pit waste disposal scenarios were considered in the analysis. The estimated advance of the production face per year was 174 m, which corresponds to a volume removed and backfilled per pit per year of 32 million bcm.

Tables 3 to 5 present the exposure factors related to temporal and spatial coincidence with failure for fixed equipment and trucks. In general, the exposure calculation of a particular equipment unit corresponds to the appropriate products of the factors in the...
three Tables, according to the fixed or traveling condition of the equipment unit and to the type of slope. Figure 11 presents sketches of the idealized pit showing the geometrical considerations made for the derivation of exposure factors at footwall and highwall slopes.

### Table 3 – Temporal Exposure Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Cycle</th>
<th>at FW</th>
<th>at HW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal</td>
<td>Fixed</td>
<td>6.5%</td>
<td>1.7%</td>
</tr>
<tr>
<td></td>
<td>Traveling</td>
<td>0.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

### Table 4 – Truck Exposure Factors (temporal)

<table>
<thead>
<tr>
<th>Truck</th>
<th>Fixed portion of cycle</th>
<th>Traveling portion of cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% fixed</td>
<td>at FW</td>
</tr>
<tr>
<td>Waste in pit</td>
<td>40%</td>
<td>1.00</td>
</tr>
<tr>
<td>Waste expit</td>
<td>20%</td>
<td>0.90</td>
</tr>
<tr>
<td>Coal</td>
<td>30%</td>
<td>0.80</td>
</tr>
<tr>
<td>Water</td>
<td>16%</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Table 5 – Spatial Exposure Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Cycle</th>
<th>at FW</th>
<th>at HW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial</td>
<td>Fixed</td>
<td>21.9%</td>
<td>18.7%</td>
</tr>
<tr>
<td></td>
<td>Traveling</td>
<td>0.0%</td>
<td>50.0%</td>
</tr>
</tbody>
</table>

Explanation of exposure factors:

**Temporal Coincidence Factors, Table 3**

For fixed equipment, the factors correspond to the ratio between the volume of the zones at risk in terms of slope failure for each type of slope (FW and HW) and the total volume worked during a year. This corresponds to the fraction of the total time of operation in a year that the equipment is within the defined zones at risk.

For fixed equipment:
FW factor = 6.5% = volume of red blocks / volume of light blue blocks (Figure 11)
HW factor = 1.7% = volume of blue blocks / volume of light blue blocks (Figure 11)

For trucks traveling:
FW factor = 0, no traffic at footwall slope
HW factor = 100%, the full width of the ramp is considered at risk, and truck factors in Table 4 are required to define exposure.

**Truck Factors, Table 4**

These factors supplement those in Table 3 and are related to the percentage of time that trucks are located in the risk zones defined. These factors are based on statistical data on actual performance of trucks at a typical pit. The fixed phase of the truck cycle is
treated in the same fashion as for fixed equipment. Distribution of fixed and traveling phases of the truck cycle is indicated in the table for each type of truck.

For trucks fixed (loading, unloading):
For both, football and highwall slopes,
Waste truck (inpit) factor = 1, the truck operates always within the pit.
Waste truck (expit) factor = 0.9, i.e. 90% of the fixed time takes place within the pit.
Coal truck = 0.8, i.e. 80% of the fixed time takes place within the pit.
Water truck = 0, the truck never stops within the pit.

For trucks traveling:
At the footwall slopes the factors are always 0 as there is no traffic at this location.
At the highwall slopes:
Waste truck (inpit) = 0.58, results in 35% of total time exposed at highwall as 60% of total operational time corresponds to the traveling phase.
Waste truck (expit) = 0.31, results in 25% of total time exposed at highwall as 80% of total operational time corresponds to the traveling phase.

FIGURE 11 – Exposure Analysis for Footwall (top) and Highwall (bottom) Slopes
Coal truck = 0.14, results in 10% of total time exposed at highwall as 70% of total operational time corresponds to the traveling phase.
Water truck = 0.12, results in 10% of total time exposed at highwall as 84% of total operational time corresponds to the traveling phase.

**Spatial Coincidence Factors, Table 5:**

These factors correspond to the percentage of length of slopes worked during a year of operation, in relation to the total length of slopes in the pit.

For fixed equipment:
FW factor = 21.9% = length of red blocks / total length of benches in FW slope.
HW factor = 18.7% = length of blue blocks / total length of ramps in HW slope.

For trucks traveling:
FW factor = 0, no traffic at FW slope.
HW factor = 50%, assumed that on average over a year, trucks utilize half the available length of ramps at the HW slope.

The equipment fleet required to operate the typical pit was established from productivity data for key equipment units and from statistical factors for support and other auxiliary equipment. The equipment fleet defined the personnel exposed to slope failures. Table 6 presents the results of the exposure analysis for personnel. A maximum exposure of 1.1% for the electric shovel operators at the footwall slope and of 13.4% for the waste truck operators at the highwall slope under a backfill scenario correspond to the critical exposures.

**Table 6 – Results of Exposure Analysis for Personnel**

<table>
<thead>
<tr>
<th>Worker description</th>
<th>Rec. No.</th>
<th>No.</th>
<th>Exposure at FW slope</th>
<th>Exposure at HW slope</th>
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<tr>
<td><strong>Waste Removal</strong></td>
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<td>Drill Operators</td>
<td>372</td>
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<td>0.2</td>
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<td>Dozer Operators</td>
<td>136</td>
<td>5</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Electric Shovel Operators</td>
<td>130</td>
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<td>Wheel Dozer Operators</td>
<td>138</td>
<td>3</td>
<td>0.8</td>
<td>0.2</td>
</tr>
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<td>Waste Truck Operators (inpit scenario)</td>
<td>108</td>
<td>25</td>
<td>0.4</td>
<td>13.4</td>
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<tr>
<td>Waste Truck Operators (expit scenario)</td>
<td>108</td>
<td>25</td>
<td>0.2</td>
<td>9.5</td>
</tr>
<tr>
<td><strong>Coal Mining</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dozer Operators</td>
<td>135</td>
<td>2</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>FELoader Operators</td>
<td>369</td>
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<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Coal Truck Operators</td>
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<tr>
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<td>2</td>
<td>1.0</td>
<td>0.2</td>
</tr>
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<td><strong>Auxiliary Equipment</strong></td>
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<td>Maintenance</td>
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<td>0.0</td>
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<tr>
<td>Geotech engineer</td>
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<td></td>
<td>0.0</td>
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</table>
4.3 Event Tree Analysis for Safety Impact of Slope Failures

Event trees were developed to estimate the probability of fatality and injury caused by the occurrence of slope failures. The event tree is a diagram that connects the starting event (failure of the slope) with the ultimate consequence under evaluation (fatality or injury) through a series of intermediate events based on a cause-effect relation. The events are quantified in terms of their likelihood of occurrence, thus enabling the assessment of the end outcomes in terms of their probabilities of occurrence, following the appropriate rules to operate the AND/OR operators.

Figure 12 shows the event trees developed for the evaluation of safety impact of failures at footwall and highwall slopes. The components of the tree addressed the following questions:

- **Are there people exposed?** The results of the exposure analysis provide the input to the answer. Higher exposure values at highwall slopes are consistent with the location of roads in this area.

- **Is monitoring effective?** The answer to this question is related to the chances of detecting failure before its occurrence. The greater effectiveness assigned to footwalls as compared to highwalls is in agreement with the character of the typical modes of failure at each type of slope.

- **Is evacuation effective?** The answer to this question is related to the chances of clearing up the site on time before the occurrence of the failure event. In the quantification of this aspect consideration was given to the relative velocities of the typical failure events at each type of slope.

- **Is there at least one fatality?** The answer to this question is related to the chances of having a fatal consequence should people and event coincide at the failure spot. The probability values assigned to the affirmative answer to this question for each type of slope considered aspects like: type of failure, expected volume of the slide, typical velocity of the failure, rate of deformation, slope angle, typical closeness of equipment and personnel to the slope and similar type of considerations.

Probability of Fatality values were estimated with the event trees for the footwall and highwall slopes. Slope management procedures and reduction of slope POF are the options available to reduce the safety impact of failures, as suggested by the event trees.

Due to the subjective character of the probability values assigned to the event components of the tree, it was felt that a sensitivity analysis of the assessment would be appropriate to establish the confidence level of the calculated probability of fatality. This was done through a Monte Carlo simulation of the event tree calculation, considering the triangular distributions illustrated in the lower right corner of Figure 12 to represent the variability of the input components.

The analysis of sensitivity was extended to the SRD at the bottom end of the event tree using the same triangular distributions for all the components of the SRD. In this way the actual distribution defined for the Total POF is incorporated into the event tree.
calculation. The cumulative distribution constructed with the thousands of calculated values enabled the estimation of the upper bound values with 90% confidence indicated at the top of the event tree.
FIGURE 12 – Event Tree for Safety Impact of FW (left) and HW (right) Slope Failure
4.4 Annual Probability of Fatality (APF) – Overall Mine

The probability of fatality values defined for the footwall and highwall slopes need to be added to define the probability of fatality representative of conditions of a pit. Furthermore, the overall mine domain is represented by seven pits; therefore, the probability of fatality for the overall mine corresponds to the addition of the values for individual pits, using the concept of system reliability.

The exposure analysis is performed on an annual basis; therefore, the probability of fatality derived from that analysis has an annual character. The actual calculated values of probability of fatality are not presented here, as the main emphasis of this paper is on the methodology followed for the assessment of safety impact of failures.

4.5 Acceptability Criteria for Safety Impact

In order to assess the meaning of the calculated probability of fatality values, they need to be compared with benchmark criteria. A typical graph used for this purpose is indicated in Figure 13 which presents acceptability criteria for fatality defined by different sources. The areas in the graph related with tolerability of risk are derived from risk guidelines developed in the United Kingdom, and correspond to risk thresholds in terms of local acceptability of deaths from industrial and other accidents. It is plotted as the number of fatalities from accidents versus the annual probability of exceeding that number.
FIGURE 13 – Benchmark Criteria for Safety Impact of Slope Failure

The “Local Tolerability Line” defines a region which is characterized by both high frequencies and severe consequences (the “Intolerable” region). The region between this line and the “Local Scrutiny Line” is a region of possibly unjustifiable risk. Between this latter line and the “Negligibility Line” is a region which is judged to be tolerable but for which all reasonably practicable steps should be taken to reduce the hazard further. This is the ALARP region (As Low As Reasonably Practicable). All combinations of frequency and number of fatalities which fall below the “Negligibility Line” are considered to be negligible (Reference 6).

The graph also contains fatality criteria developed by the dam engineering discipline, which is of interest as benchmark criteria, because it is based on a conservative approach to risk, since the consequences of dam failures are so devastating. Of particular interest is the single fatality at an annual probability of $10^{-4}$ identified as “The proposed BC Hydro individual risk”. This number represents the risk exposure to ‘natural death’ by the safest population group in North America aged between 10 to 14 years within a person’s life cycle. The interpretation is that 1 in 10 000 persons between the ages of 10 and 14 years will die every year from natural causes. This is also popularly accepted as the boundary between voluntary and involuntary risk. Accepting this as a criteria for slope design, implies, therefore, that a person subjected to the open pit working environment is not...
exposed to greater death risk resulting from a slope failure than he is of dying due to natural causes.

The comparison of the calculated APF for Cerrejon with the acceptability criteria indicated that highwall slope stability is the key aspect in terms of risks to personnel safety, as the APF for the overall mine greatly depends on highwall slope conditions, and it is rather insensitive to changes in the design conditions of the footwall slopes.

The calculated APF for Cerrejon falls within the ALARP region, which is a result consistent with the level of information available for design and the stage of development of the project. The points plotted for more than one fatality in Figure 13 are the result of a collective fatality calculation based on assumptions of gang sizes exposed.

To help in the interpretation of the APF defined for Cerrejon, some statistics on fatalities in the mining industry and in other areas are presented in a form that can be compared with the risk of fatality. Statistics on fatal incidents were used to calculate the Fatal Accident Rate (FAR), defined as the number of fatalities per thousand employees working their entire life (assumed to be 50 years). Thus the FAR is based on $10^8$ total hours. The annual individual risk can be also calculated from the FAR value. The information is presented in the form of a plot of FAR versus the annual individual risk in Figure 14. This graph suggests $10^{-4}$ as a lower bound value for annual individual risk in terms of performance of the mining industry in various regions.

4.6 Option for Mitigation of Safety Impact of Slope Failures

Risk mitigation can be achieved by reduction of the consequences of slope failure and by reduction of the POF of the slope. Risk mitigation options should be sought initially by reducing the consequences of slope failure. In this case the inspection of the event tree diagrams used for impact assessment of slope failures enable the identification of the more appropriate aspects to be treated from a cost-benefit point of view. An example of this would be the improvement of monitoring systems and evacuation procedures.

If the reduction of the consequences of slope failure is not sufficient to mitigate the risks to acceptable levels, options based on reducing the Design POF of the slope may be required. These options include the reduction of uncertainties contributing to the total POF of the slope or adjustments to slope design.
5. RISK ANALYSIS OF SLOPE FAILURE – ECONOMIC IMPACT

5.1 Objective

The objective of this task was the assessment of the consequences of footwall and highwall slope failure in terms of economic losses associated with impact on equipment. This was done through the estimation of the probability of occurrence of these losses and their costs. The cost of losses is estimated from the costs of damaged equipment, lost production, and site restoration.

5.2 Exposure Analysis of Equipment

The purpose of this analysis was to estimate the probability of coincidence in time and space of equipment operating in the pits with eventual slope failures. The main considerations and assumptions for this analysis were presented and discussed in Section 4.2, as the personnel exposure evaluation was based on equipment exposure. Therefore, the same exposure factors presented in Tables 3, 4 and 5 are applicable for this analysis, which produce the same exposure values presented in Table 7. However, in this case these factors are assigned to the equipment rather than to the operators. The issue of relative size of the subject (equipment or people) being impacted by a failure, in relation to the size of the slide, is addressed with the last question in the event trees.
5.3 Event Tree Analysis for Economic Impact of Slope Failures

The event tree analysis for the assessment of impact of slope failures on equipment is very similar to that described for safety impact. However, in this case the questions refer to equipment rather than to personnel. Figure 15 shows the event trees for impact on equipment developed for footwall and highwall slopes.

The probabilities of economic loss calculated with these event trees, refer to the equipment units with the maximum exposure at each slope, i.e. an electric shovel at the footwall slope and a waste truck at the highwall slope. However, a meaningful evaluation of the economic impact due to equipment loss requires the consideration of various possible situations which are discussed in the following section.

5.4 Probability of Economic Impact – Overall Mine

In order to assess the probability of occurrence of an economic loss due impact of failures on equipment for the overall mine situation, typical groups of equipment at footwall and highwall slopes were considered as indicated in Table 7. These groups of equipment, called equipment modules in the table, were evaluated in terms of the estimated cost of the impact and its probability of occurrence. Then modules of similar cost of impact at Footwall and Highwall slopes were selected to assess the probability of that economic loss for the overall mine.

The costs of the impacts were calculated as the sum of the cost of replacement of the equipment, the cost of lost production and the cost of cleaning the site.

The cost of replacement was assumed to be the capital cost of purchase affected by a factor related to the level of impact.

The cost of lost production was calculated as the product of the time of replacement of equipment in Months, the productivity of the unit in Tons of coal per Month and the profit margin in US dollars per Ton corresponding to an assumed coal price. Time of replacement was estimated as the purchase time in Months, affected by the factor related to level of impact described before.

The cost of cleaning the site was calculated from the operational cost of the auxiliary equipment required for this activity and the estimated volumes of typical failures.

The results presented in Table 7 indicate that impacts on shovels have a greater economic consequence and a smaller probability of occurrence than impacts on trucks. The cost of impacts on shovels is in the order of 25 million dollars, whereas impacts on trucks cost about 4 million dollars.
To calculate the probabilities of having these economic losses for the overall mine, modules of similar cost of impact at footwall and highwall slopes were combined to represent the mine situation. In general results indicated that lower impact but more frequent events are driven by highwall slope failures impacting trucks; whereas, higher impact but less frequent events are driven by footwall and highwall slope failures impacting shovels.
FIGURE 15 – Event Trees for Impact on Equipment of FW (left) and HW (right) Slope Failure
Table 7 – Cost of Slope Failure Impact on Typical Equipment Modules

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<td></td>
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<tr>
<td>Electric Shovels 27.5 cum (P&amp;H 2800XPB)</td>
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<td>70%</td>
<td>4.413</td>
<td>10.5</td>
<td>16.715</td>
<td>1.08</td>
<td>2.9E-06</td>
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<td>0.492</td>
<td>6.3</td>
<td>16.715</td>
<td>1.08</td>
<td>2.9E-06</td>
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<td>70%</td>
<td>2.706</td>
<td>6.3</td>
<td>16.715</td>
<td>1.08</td>
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<td>2.706</td>
<td>6.3</td>
<td>1.541</td>
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<td>70%</td>
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<td>Typical Equipment Modules impacted by HW Slope Failure</td>
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NOTE: (1) Calculation based on an hypothetical coal sale price used for demonstration purposes only.

5.5 Option for Mitigation of Economic Impact of Slope Failures

Risk mitigation options similar to those discussed in Section 4.4 for safety impact are also applicable to mitigate the risk of economic losses. In general, the potential economic losses associated with impacts on trucks could be more effectively mitigated with measures related to management of highwall slope failures.

6. CONCLUSIONS

Some relevant conclusions from this study are:

1. The risk assessment process applied to the Cerrejon mine, using the available information on mine plan, geotechnical conditions, slope design and engineering judgment on the assessment of the various components of the model, has shown how the system can be applied to evaluate and mitigate the consequences of failure in respect of personnel, equipment and economics pertaining to mine design procedures.
2. The system provides the opportunity to quantify the risks and mitigation measures for a design approach based on accepting slope failures, and as such, it can be an extremely powerful tool in the mine design process.

3. It also provides the opportunity to rationalize the geotechnical information requirements, once the risk criteria have been defined by management.

4. In terms of safety of personnel, the results indicated that the impact of failures is driven by highwall slope stability and is essentially unaffected by changes in the likelihood of footwall slope failures.

5. An effective reduction of the annual probability of fatality can be achieved through improvements in the performance of system for detection and warning of highwall slope failures.

6. In terms of economic loss, results suggested that impacts of slope failures on equipment can be categorized as: low impact but associated to more likely event occurrences for trucks, and high impact but related to less probable event occurrences for shovels.

7. The probability of low impact events is driven by highwall slope failures impacting trucks; therefore, an effective reduction of the likelihood of these events can be achieved through improvements in the effectiveness of the systems for detection and warning of highwall slope failures.

8. The probability of high impact events is driven by footwall and highwall slope failures impacting shovels; therefore the management of these risks can be achieved with measures at both types of slope.

7. REFERENCES

1. “Hazard Identification, Risk Assessment and Risk Control – MIHAP No.3”, Major Hazards Unit, Dep. of Urban and Transportation Planning, Sydney, Australia, May 2003, Consultation Draft, Version A.


