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Risk Evaluation of Slope Failure at the Chuquicamata Mine

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Abstract

The possibility of increasing the pit slope angles of the Chuquicamata Mine as the pit approaches its planned closure is being considered. Compared to the conventional mine design, the slope steepening is understood to raise the net present value (NPV) of the mine, but also, attracts an increase in possible adverse outcomes related to the increase in the likelihood of slope failures. A quantitative risk evaluation was undertaken to provide information to assist the mine management in their decision by: defining risks in terms of safety and economics, quantifying risk level for different slope configurations and comparing results against industry norms.

The approach included three main tasks: (1) evaluation of the total probability of failure (POF) representative of the stability conditions of slopes. (2) Evaluation of the consequences of slope failure on safety of personnel. (3) Evaluation of the consequences of slope failure in terms of economic losses associated with impact on equipment and production, including the Force Majeure event situation (major economic loss affecting the continuation of the mine business). Options for risk mitigation are also discussed briefly.

The main purpose of this paper is to present the process of a risk evaluation of mine slopes; 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 the mine's geotechnical department during the years 2004 to 2006, with the support of various consultants, with the main objective of providing the management with the appropriate information to base decisions on the best slope steepening scenarios to be developed.

The main objectives of the study were: (1) to assess the impacts of slope failure in terms of safety and economic consequences; (2) to define the need for risk treatment by benchmarking the calculated impacts and comparing with acceptability criteria; and (3) to identify the key aspects to consider in a risk treatment plan.

The methodology included three main tasks: (1) evaluation of the probability of failure (POF) representative of the stability conditions of pit slopes; (2) evaluation of risk associated with safety of personnel that might be impacted by the occurrence of slope failures; and (3) evaluation of risk associated with economic losses derived from impact on equipment and on production.

The results of these analyses enabled the identification of risk mitigation options for those situations where acceptability criteria are exceeded.

2 Factor of safety, probability of failure and risk analysis

2.1 Uncertainties in slope design

The optimum design of a pit requires the determination of the most economic pit limit which normally results in steep slope angles as in this way the excavation of waste is minimised. In general as the slope angle becomes steeper, the stripping ratio (waste to ore ratio) is reduced and the mining economics improves. However, these benefits are counteracted by a reduced stability of the slopes and the consequent increased risk to the operation. Thus the determination of the acceptable slope angle is a key aspect of the mine business.

The difficulty in determining the acceptable slope angle stems from the existence of uncertainties associated with the stability of the slopes. Table 1 summarises the main sources of uncertainty in pit slopes. These uncertainties are accounted for during the process of design of the slopes and different methodologies have been used for this purpose.

The uncertainty might be due to a random variability of the aspect under analysis or to lack of knowledge of that aspect. Field data collection and site investigations are used to reduce these uncertainties and to define the inherent natural variability.

Table 1 Sources of uncertainty in pit slopes

Slope aspect	Source of uncertainty
Geometry	Topography / geology / structures / groundwater surface
Properties	Strength / deformation / hydraulic conductivity
Loading	In situ stresses / blasting / earthquakes
Failure prediction	Model reliability

Steffen (1997) has proposed a categorisation of pit slope angles based on the confidence of slope design, which in turn depends on the degree of certainty which applies to the data available. The categories define proven, probable and possible slope angles according to a decreasing level of certainty in the design.

2.2 Factor of safety approach

The oldest approach for slope design is that based on the calculation of the factor of safety (FOS). The FOS can be defined as the ratio between the resisting forces (strength) and the driving forces (loading) along a potential failure surface. If the FOS has a value of one, the slope is said to be in a limit equilibrium condition, whereas values larger than one correspond to stable slopes. The FOS approach is a deterministic technique of design as a point estimate of each variable is assumed to represent the variable with certainty. The uncertainties implicit in the stability evaluation are accounted for through the use of a FOS for design larger than one. This acceptability criterion is intended to ensure that the slope will be stable enough to have a safe mining operation. Traditionally a FOS of 1.3 has been used as the acceptable value for pit slope design. This criterion is based on results of back analysis of slopes at a particular mine site as reported by Hoek and Bray (1974). Figure 1 shows the results of this study, which suggests that a FOS of 1.3 would reasonably predict stable slopes.

There are two main disadvantages of the FOS approach for slope design. First, the acceptability criterion is based on a limited number of cases and combines the effect of many factors that makes it difficult to judge its applicability in a specific geomechanical environment. Second, the FOS does not provide a linear scale of adjudication of the likelihood of slope failure. This will be discussed in the following section.

2.3 Probability of failure approach

In recent years probabilistic methods have been more frequently used in slope design. These methods are based on the calculation of the probability of failure (POF) of the slope. A probabilistic approach requires that a deterministic model exists. In this case the input parameters are described as probability distributions rather than point estimates of the values. By combining these distributions within the deterministic model used to calculate the FOS, the probability of failure of the slope can be estimated. A technique commonly used to combine the distributions is the Monte Carlo simulation. In this case each input parameter value is sampled randomly from its distribution and for each set of random input values a FOS is calculated. By repeating this process many times, a distribution of the FOS is obtained. The POF can be calculated as the ratio between the number of cases that failed (FOS<1) and the total number of simulations. The POF concept is illustrated on Figure 2.

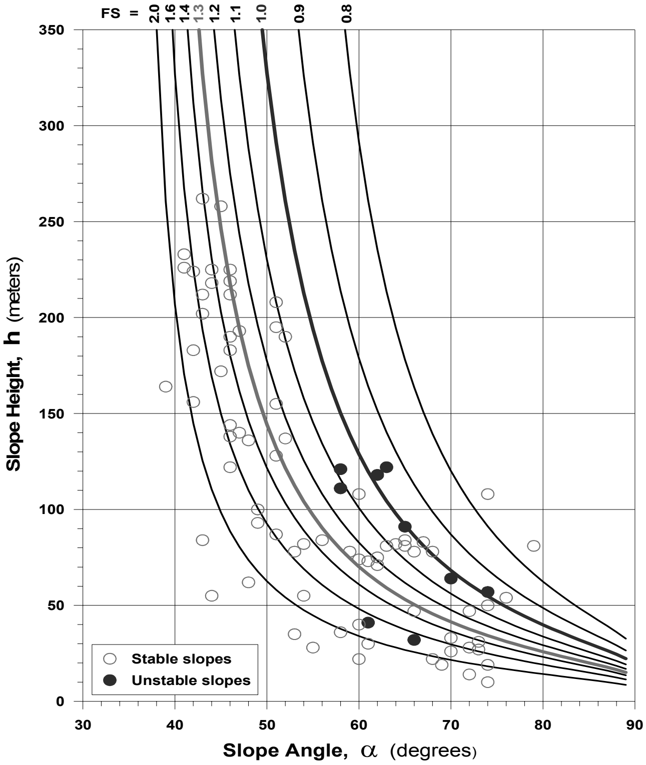


Figure 1 Cases of rock slope with failures and non-failures distinguished (Hoek and Bray, 1974)

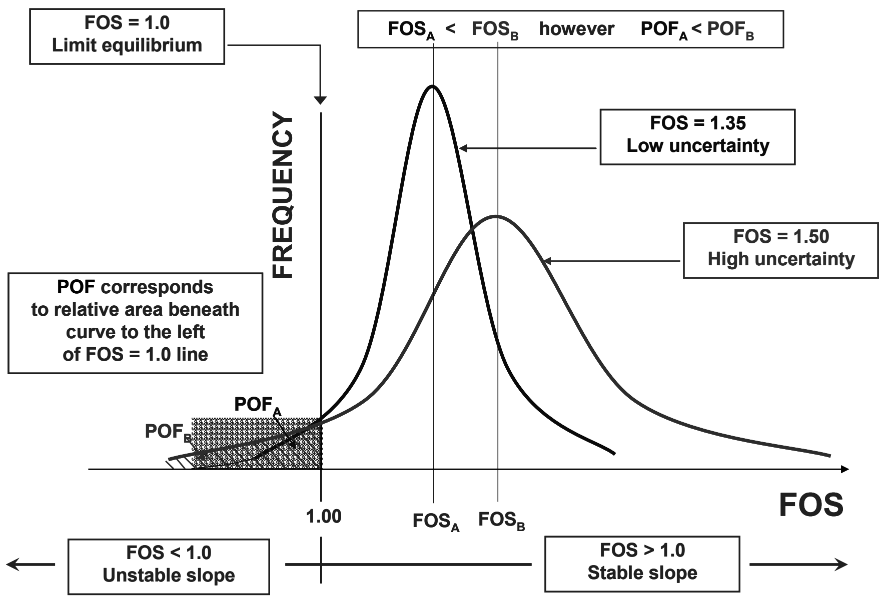


Figure 2 Definition of POF and Relationship with FOS according to uncertainty magnitude

The advantage of the POF over the FOS as a stability indicator is illustrated on Figure 2. By definition, there is a linear relationship between the POF value and the likelihood of failure, whereas the same is not true for the FOS. A larger FOS does not necessarily represent a safer slope, as the magnitude of the implicit uncertainties is not captured by the FOS value. A FOS of 3 is not twice as stable as a FOS of 1.5, whereas a POF of 5% is twice as stable as a POF of 10%.

Some drawbacks of the FOS methodology that persist in the POF approach are the difficulties to define an adequate acceptability criterion for design and the limitations to predict failure with the underlying deterministic model.

Acceptable criteria for POF has been defined by some researchers as indicated in Table 2 (extracted from Sjoberg (1999)). However, these criteria should be considered of reference. As pointed out by Sjoberg (1999), the actual criteria to be used in a specific mine cannot be determined from general guidelines like these; they should be subject to a more thorough analysis of the consequences of failure.

Table 2 Acceptable POF criteria for rock slopes

Category and consequence of failure	Example	POF (FOS<1) %
Not serious	Non critical benches	10
Moderately serious	Semi permanent slopes	1–2
Very serious	High/permanent slopes	0.3

2.4 Risk analysis approach

The risk analysis approach tries to solve the main drawback of the previous methodologies with regard to the selection of the appropriate acceptability criteria. Risk can be defined as the probability of occurrence of an event combined with the consequence or potential loss associated with that event:

$$\text{Risk} = P(\text{event}) \times \text{Consequence of the event}$$

In the case of slopes, the P(event) is the POF of the slope and the consequences can be two fold: personnel impact and economic impact.

The POF calculated as part of the design process is normally based on a slope stability model calculation and accounts only for part of the uncertainties of the slope. Because the risk analysis sets the acceptability criteria on the consequences rather than on the likelihood of the event, a thorough evaluation of the POF of the slope is required, incorporating other sources of uncertainty not accounted for with the slope stability model. For this purpose and for the analysis of consequences of slope failure, non formal sources of information (engineering judgment, expert knowledge) are incorporated into the process with the aid of methods such as development of logic diagrams and event tree analysis. These techniques are described in more detail in specialised books on reliability methods in geotechnical engineering such as those by Baecher and Christian (2003) and Vick (2002).

In the following sections a description of the specific approach followed for the Chuquicamata mine study is presented.

3 Approach of risk analysis at Chuquicamata

There are many methods available for developing a risk consequence process. However, they all contain some common steps, as described in the guidelines by the Australian Geomechanics Society (2000). 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 determine the 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 this paper refers mainly to the steps 2 to 5 of this methodology, applied to the risk assessment of the pit slopes for the Chuquicamata mine.

The risks associated with a major slope failure can be categorized by the following consequences: (1) injury to personnel; (2) damage to equipment; (3) economic impact on production; (4) force majeure (a major economic impact); (5) industrial action; and (6) 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. Commercial 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. Safety risks are usually regarded as outside management discretion with most companies seeking compliance with industry norms or other indicators of societal tolerance.

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 four consequences.

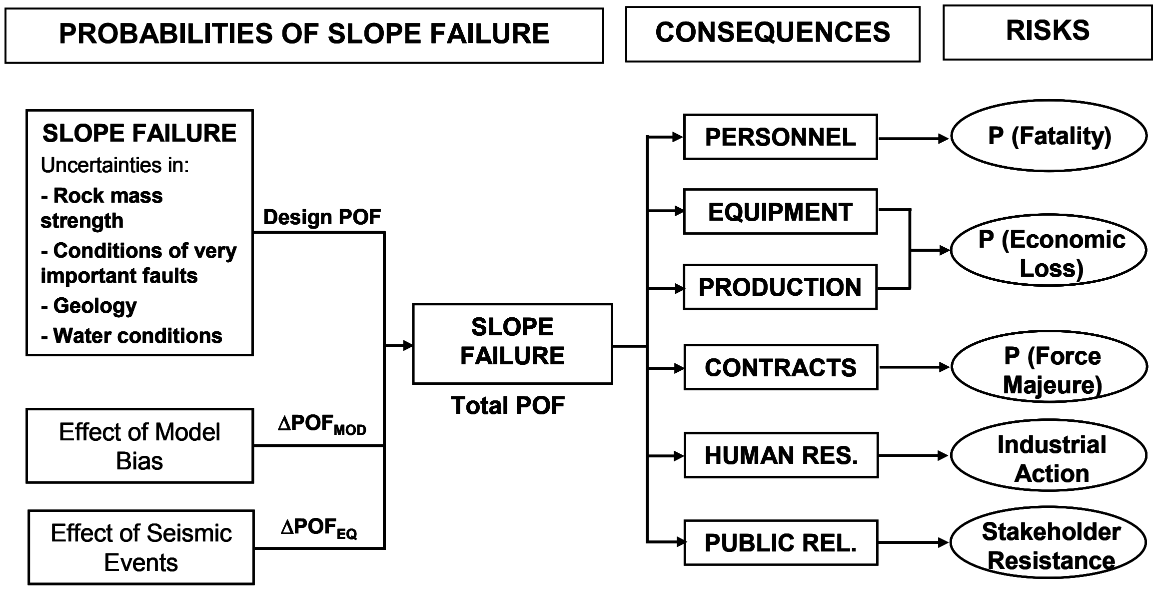


Figure 3 Methodology for risk evaluation of pit slopes

In particular the study consisted of three main tasks: (1) evaluation of the probability of failure (POF) of pit slopes; (2) consequence analysis in terms of impact on safety of personnel; and (3) consequence analysis in terms of economic impact. In the following sections these tasks will be described in detail.

4 Probability of slope failure

4.1 Objective

The objective of this task was the assessment of the likelihood of occurrence of slope failure events that might impact on personnel and equipment. This was done through the estimation of the probability of failure representative of the stability conditions of the slopes.

Possible slope failures have been considered at three levels: global, in which the entire pit wall might collapse jeopardising the entire mine; inter-ramp, in which a partial wall failure might substantially affect the recovery of ore; and bench, in which slope failure only affects the local operations in the vicinity of the failed bench.

In order to account for different failure modes at each of these scale, several different analysis techniques were used to calculate failure probabilities, as discussed below.

4.2 Site description

The Chuquicamata mine orebody is located in the Chuqui Porphyry complex and occurs east of the major north/south trending crustal fault known as the ‘west fault’. The open-pit slope performance is distinctly different in the west and east slopes.

The west slope is intersected near the toe by the west fault and an associated shear zone west of the fault, comprised of altered and much weaker rock. This zone can vary in width from 1 m in the northern part of the pit to 100 m in the southern part. In the extreme northern part of the pit, the shear zone relocates to the east of the fault, but does not display the same degree of rock disturbance as that on the west of the fault. As a result of this shear zone, the west slope is in constant deformation, and the rock mass behaves as a disaggregated rock with creep or plastic deformation-type failure.

In contrast, the east slope is supported in the toe by very competent rock and behaves in a brittle mode during failure. Displacements observed in the east are of an elastic response type to mining, with the potential for sudden large strains in the event of failure.

As well as the basic division of the rock behaviour between the east and west slopes, there are differences in structure and properties on a finer scale.

The mine has been divided into seven zones, shown on Figure 4, each of which is geotechnically similar (including rock mass properties, major features, rock types and alteration). However, while the rock mass properties can be assumed to be representative within the domain, significant changes of slope orientation within the domain require separate analysis as design sectors. There are, therefore, fifteen design profiles distributed amongst the seven zones.

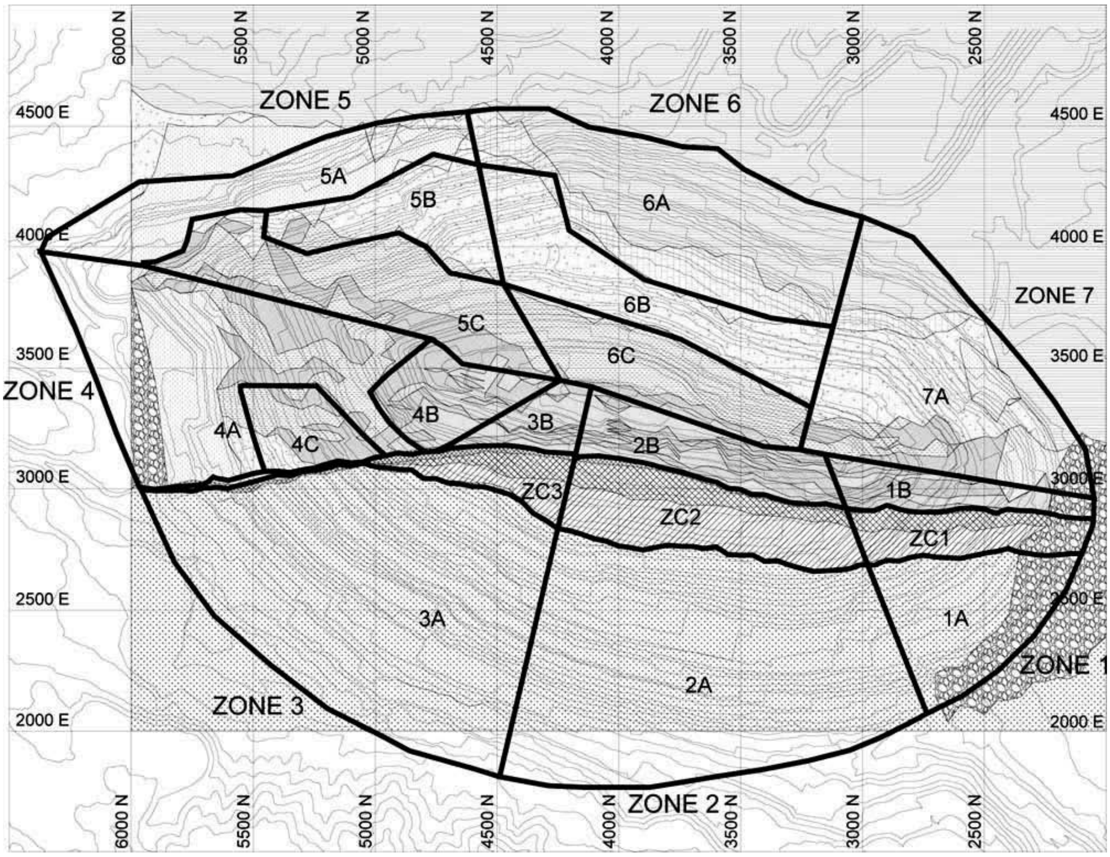


Figure 4 Plan view showing geotechnical units and geomechanical zones

Behaviour in each zone is assumed to be independent of the situation in adjacent zones. This is justified on the basis that slides at the pit have tended to be narrower than their length. In general, it has been observed that the width of the failing zone is about one-third the length of the failing region as measured from rear scarp to toe along the face of the slope. This type of failure geometry makes it likely that the rock behaviour in the identified zones can be treated as being independent.

4.3 Slope geometries

The effective change in geometry is indicated in the east-west cross-section shown on Figure 5. The different slope geometries correspond to the different mining options. Alternative plans to the reference plan incorporate different levels of scavenging exposed ore in the bottom of the reference plans and result in the effective steepening of the slope at the toe. This is achieved by double-benching the faces from different stages of the pit development sequence. As seen from the figure, the proposed slope design involves inter-ramp slope increases of 2 to 5° and about a 5% increase in overall slope height.

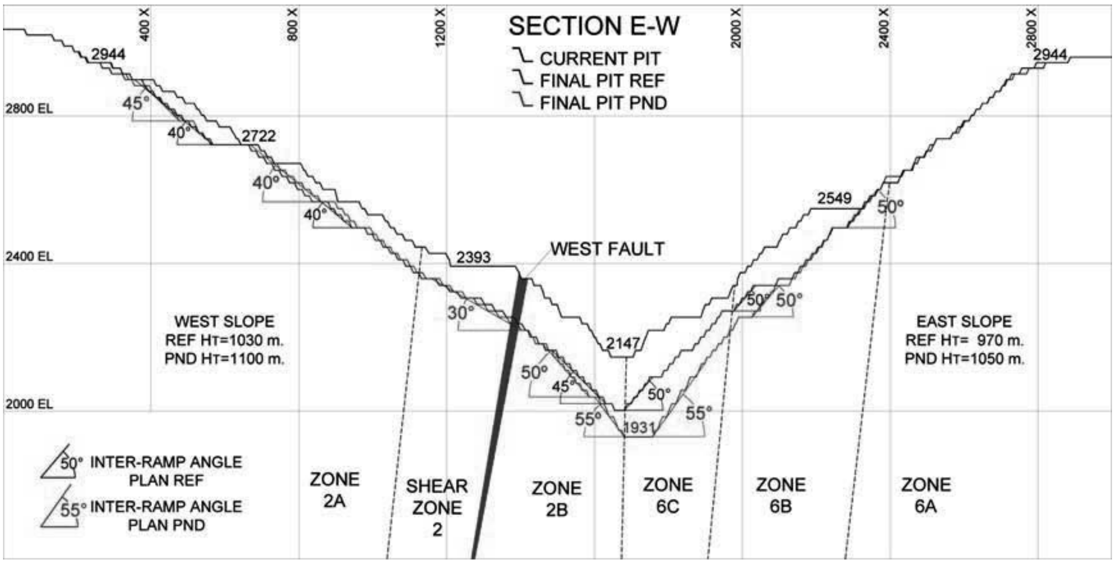


Figure 5 Comparison of current and proposed pit slopes

4.4 Global slope failure

4.4.1 Overview

The probability of failure (POF) of the slopes was estimated with a methodology that uses available data on slope properties and considerations based on expert judgment to account for other sources of uncertainty of the stability of the slope. Results of factor of safety calculations made with UDEC slope stability models are used to define, through a Monte Carlo (MC) simulation, a FOS distribution reflecting the variability of the uncertain input factors. The MC analysis is performed outside the stability model with a procedure often referred as the response surface method.

Six principal uncertainties were considered for the evaluation of the probability of failure:

- Rock strength deviation. Represented by the variability of UCS and GSI parameters. The actual rock strength in the slopes being different (both weaker and stronger) than the values used in designing the slopes.
- Structural feature deviation. Represented by the variability of strength and orientation of structures. The larger scale features being different, in both position and strength, from the design characterisation.
- Geological deviation. The difference between the actual lithological contacts of the different geotechnical units and those in the design characterisation.
- Groundwater pressure deviation. The difference between the expected groundwater pressures and those that may occur (higher pressures reduce slope stability).
- Seismic loading. The effect of exceptional earthquake events on the mine slopes.
- Model reliability. Represented by the variability of FScrit (defined as the FOS corresponding to the failure condition of the slope). The degree to which the design methods can be relied on as the slope design approaches its limit of stability.

4.4.2 Factor of Safety (FOS) calculation

Using UDEC, the factor of safety was determined by first allowing a bench excavation simulation to come to equilibrium. Then, both cohesion and frictional strengths were reduced simultaneously by a strength reduction factor (SRF). Reduction in strength continued until onset of accelerating movements, which were taken as indicating failure. The factor of safety was taken as the inverse of the strength reduction factor.

4.4.3 Monte Carlo analysis with response surface methodology

Ideally, the factor of safety distribution would be computed by the Monte Carlo method, which allows direct representation for the various uncertainties that are to be represented. In this technique, many simulations ('realisations') are made using randomly chosen properties from the parent distributions for the various uncertainties ('assumptions') represented in the analysis, with the results added to give a probability distribution of the computed factor of safety. Typically, several thousand realizations will be made to determine ('forecast') the probability of performance modelled. Realistically, the Monte Carlo approach cannot be used directly with numerical analyses in the UDEC code, as each simulation in UDEC takes up to a day. Instead, an approximate approach was adopted, often referred to as the response surface method (e.g. Morgan and Henrion, 1990), which fits curves to UDEC results. These fitted curves then are used in the Monte Carlo analysis. Using the response surface method, the distribution of the factor of safety for a slope can be estimated using a few UDEC runs per slope.

The present work has represented six uncertainties within a response surface framework: (1) uncertainty in characteristic GSI; (2) uncertainty in characteristic UCS; (3) uncertainty in orientation of very important faults; (4) uncertainty in shear strength of very important faults; (5) uncertainty in groundwater pressures; and (6) uncertainty in geologic unit boundaries.

In the response surface method, with six uncertainties (denoted as x1- x6) contributing to the distribution of FOS, this distribution could be viewed as being represented by a function

$$FOS = R(x_1, x_2 .. x_6) \quad (1)$$

In six-dimensional space, defined by variables x_1- x_6, R can be viewed as a surface. The response surface method assumes that the effects of each variable x_i on FS are independent of the other variables. Inaccuracies arise because this assumption is not true in general. However, these inaccuracies are minimised by calculating the best-estimate of FOS first using the best-estimates for each of the uncertainties $x'_1, x'_2 ... x'_6$:

$$FOS_{bc} = R(x'_1, x'_2 \dots x'_6) \quad (2)$$

where FOS_{bc} is the best-estimate value and is referred to as the *base case*. Next, the change in FOS caused by change in each of the uncertainties is investigated in turn and while keeping the remaining five at their best-estimate values. An effect factor β is defined for each of the uncertainties where

$$\beta(x_1 - x'_1) = R(x_1, x'_2 \dots x'_6) / FOS_{bc} \quad (3)$$

similarly for the other uncertainties by cyclic rotation of the indices. One point on either side of the best-estimate value (referred to as the "+" and "-" cases) is used to determine the β trends and is fitted with a 2nd order polynomial function, as illustrated on Figure 6.

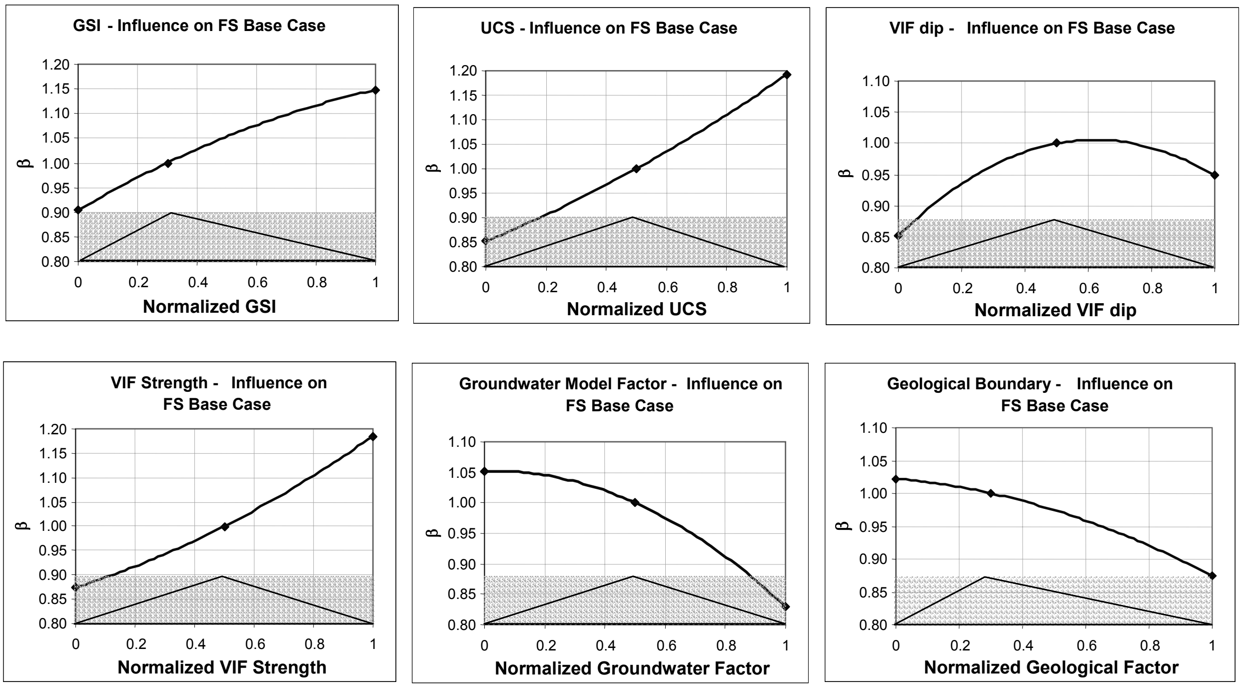
Multiple Monte Carlo simulations, using the various representations of the uncertainties (typically triangular), then allow estimation of the distribution in the factor of safety using:

$$FOS = FOS_{bc} \,.\, \beta(x_1 - x'_1) \,.\, \beta(x_2 - x'_2) \dots .\, \beta(x_6 - x'_6) \quad (4)$$

4.4.4 Model uncertainty

Model uncertainty arises through systematic biases in input parameter determinations and idealisations in the calculation vehicle, leading to the effect that failure occurs for some critical factor of safety that may not be unity. Bias in parameter determination is inevitable, and is handled by calibration to slope performance. Model idealisations arise from representing a 3-D situation with a 2-D model, representing the rock mass strength with an elastic-plastic model etc. Some aspects of model idealisation will tend to reduce FScrit while other aspects might raise FScrit. The effect of the parameter bias and model uncertainty is to produce an uncertainty band that is centred on the underlying bias.

Traditionally model uncertainty has been accounted for in the choice of acceptable factors of safety. Acceptability criteria have been based on the approach of comparing slope angle with slope height from actual successful and failed slopes. This approach was used in the study of Hoek and Bray (1974) that produced the results indicated in Figure 1, and more recently, in a similar investigation by Sjoberg (1999) with the introduction of a measurement of the rock strength.



$$FOS_i = FOS_{base\_case} \cdot \beta 1_i \cdot \beta 2_i \cdot \beta 3_i \cdot \beta 4_i \cdot \beta 5_i \cdot \beta 6_i$$

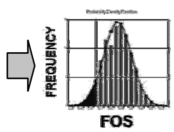


Figure 6 Illustration of derived influence coefficients β for response surface

The three main difficulties of this approach are: (1) it does not recognize bias in the characterisation of data from one slope to another, (2) structures and scale related features that might affect each slope are not represented and (3) different failures modes are not recognised. However, all the studies confirm the existence of model uncertainty and suggest that there is a range for FScrit.

An alterative to looking at FScrit directly is to look at the actuarial failure rates versus nominal factor of safety. A risk evaluation study carried out by Golder Associates in 1997 (described by Pine and Roberds, 2005) for a highway widening in Hong Kong enabled the estimation of failure probability from actual proportion of failures. Results of this study are shown on Figure 7 as trends of FOS versus POF. The Hong Kong trend is biased as the engineers involved in the work noted that conservative strength estimates were used. Nevertheless, the trend line indicates 100% confidence in failure at a nominal FScrit=0.8. Hoek and Bray's data on Figure 1 can be converted to a similar form by counting the number of failures at a given nominal FOS versus the number of cases in the database and assuming that the data shown on the figure is a representative sample. The results of this conversion are also plotted on the graph at the left of Figure 7 and also indicate 100% confidence in failure at a nominal FScrit = 0.8.

The definition of the FScrit distributions has two aspects; one is the selection of the best estimate value, and the other is its assumed variability.

In terms of the best estimate value of FScrit it was considered that the departures from 1.0, which is the value normally assumed to represent failure, would be better justified by the calibration of the stability model based on results from back analysis of failures. Therefore, results of a few available back-analyses of past slope failures in the pit with the UDEC model using present best estimates of rock parameters and conditions were used to define initial values of FScrit. These values then were adjusted on the basis of engineering judgment and benchmarking of results of the FOS versus POF relationships derived from other studies as described before. The graph at the right of Figure 7 shows an example of the results of the benchmarking analysis, for the case of global slopes assuming an FScrit of 1.05.

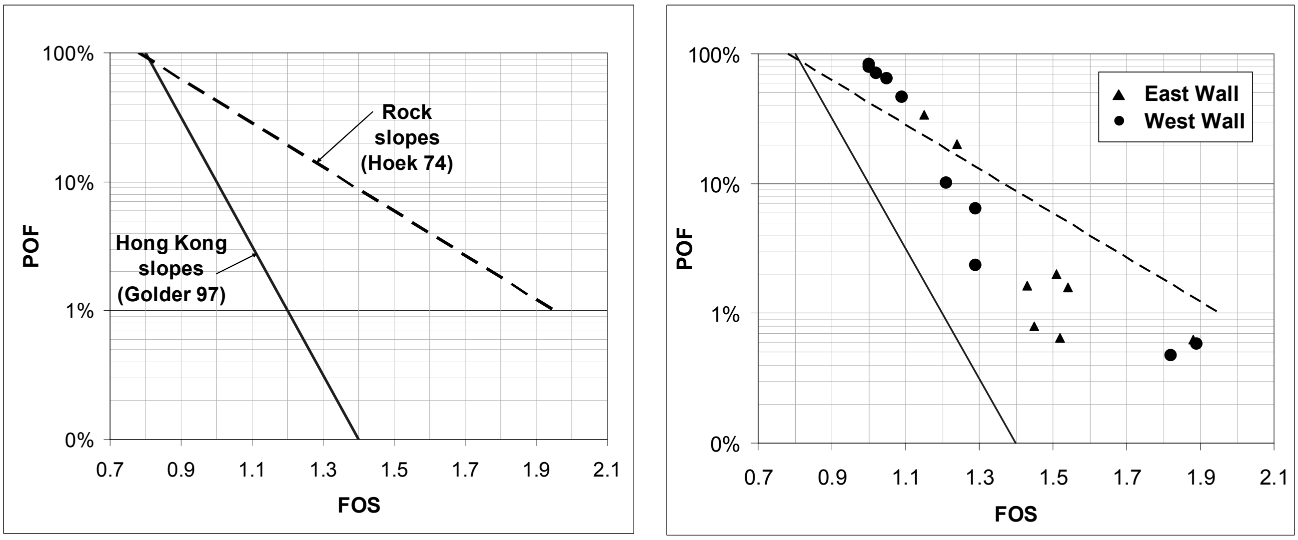


Figure 7 Computed FOS versus probability of slope failure from various studies (left) and benchmarking of Chuquicamata data for best estimate value of FScrit (right)

The variability of FScrit was chosen from engineering judgment at 5% given the generalised use of the UDEC model for the design of large rock slopes and considering that this model has undergone intensive benchmarking against the actual performance of the Chuquicamata slopes.

The estimated model uncertainties finally used in the risk evaluation for the east and west slopes at each of inter-ramp and global scale are summarised on Table 3. These model uncertainties are consistent with the characterisation parameters and groundwater conditions used for the slope stability analyses.

Table 3 Distributions for FScrit

Scale	East slope	West slope
Inter-ramp	T[1.14, 1.20, 1.26]	T[1.05, 1.10, 1.16]
Global	T[1.00, 1.05, 1.10]	T[1.00. 1.05, 1.10]

Note: Values define triangular distributions

4.5 Inter-ramp failures

Three modes of inter-ramp failure were considered: (1) rock mass failure (analysed with FLAC); (2) daylighting wedge failure (analysed with SWEDGE); and (3) non-daylighting wedge failure (analysed with FLAC3-D). The response surface method described above was used to calculate failure probabilities for each of the three failure modes.

4.6 Bench failures

Bench-scale failures are dominated by structural considerations, day-lighting wedges or planar failures. The probability of failure is determined by directly using the measured distributions of discontinuity data to calculate the probability of wedge and planar-failure potential. A kinematics-based analytical model was used in the 'probability' mode to determine directly the probabilities of failure using a normal distribution function to represent the defect data sets.

5 Risk analysis of slope failure – safety impact

5.1 Objective

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

5.2 Event tree analysis for safety impact

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 8 shows the typical event tree developed for the evaluation of safety impact of slope failures. The components of the tree addressed the following questions:

- Does visual inspection detect movement?
- Is there sufficient warning from visual alert?
- Is the instrumentation system operational?
- Is there sufficient warning from system alert?
- Do monitoring people respond correctly?
- Is the evacuation procedure successful?
- Are there people exposed?
- Is there at least one injury?
- Is there at least one fatality?

The probability values assigned to the answers to this question are the reflection of aspects like: type of failure, expected volume of the slide, typical velocity of the failure, rate of deformation, slope angle, typical proximity of equipment and personnel to the slope and similar type of considerations.

Due to the subjective character of the probability values assigned to the event components of the logic diagram, it was felt important to recognise uncertainty in these judgmental probabilities. This was done by using symmetrical triangular distributions with a maximum absolute variability of ±20%, as illustrated in Figure 9, to represent the uncertainty of the input components.

5.3 Exposure analysis of personnel

The probability of coincidence in time and space of mine personnel with an eventual slope failure was estimated for the scenario in which people had not been evacuated for the various possibilities shown in the logic diagram. The approach uses information on pit layout, equipment fleet and personnel working during the year. The geotechnical zones shown on Figure 5 were also used for the assessment. Exposure factors are then estimated based on the geometry of the pit and the statistical data on the actual performance of equipment. Exposure of operating personnel is established from that of equipment, as well as supervisory, service and technical personnel exposure to slope failures during the course of normal operations.

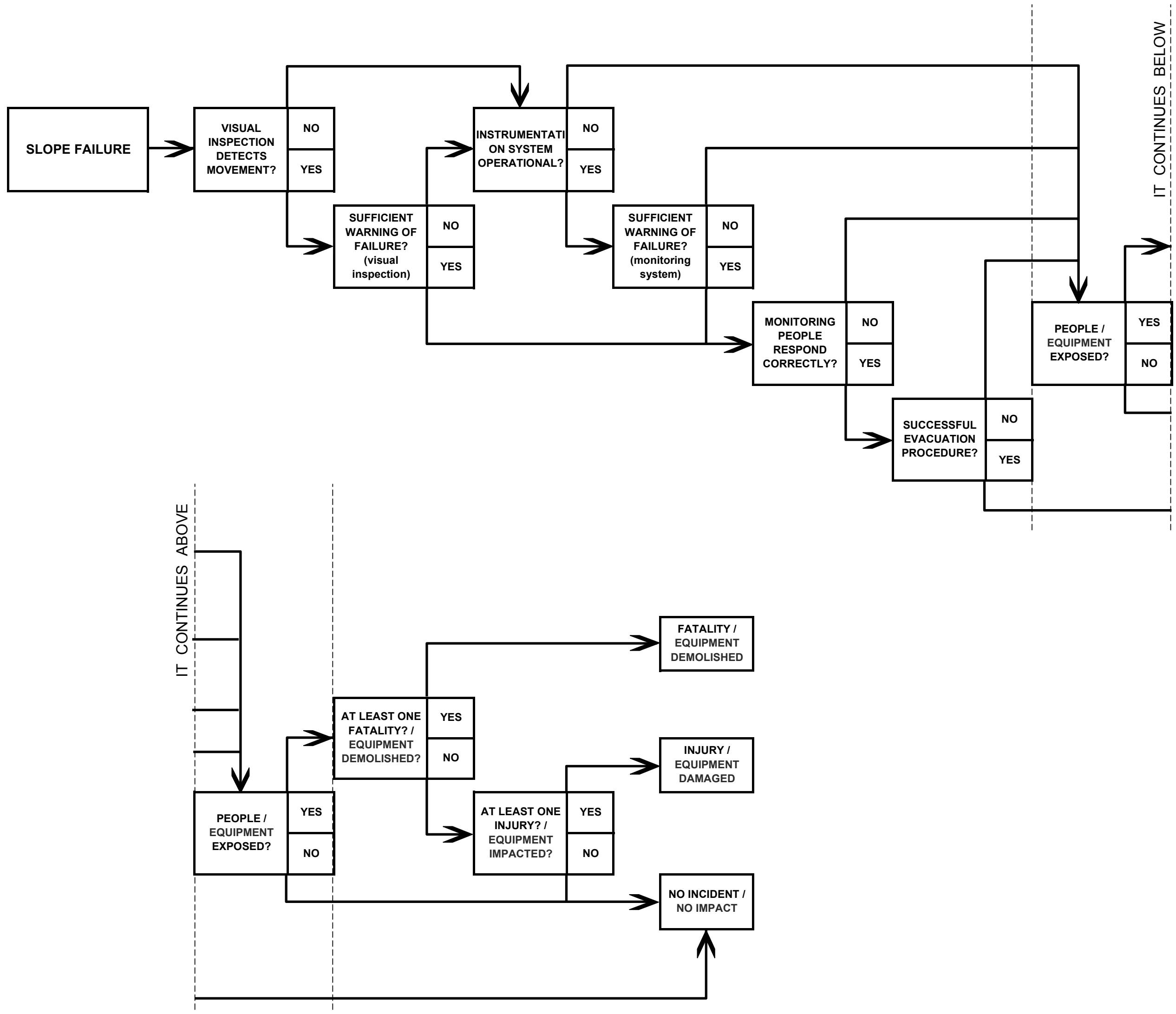


Figure 8 Event tree diagram for evaluation of safety and equipment impact of slope failures

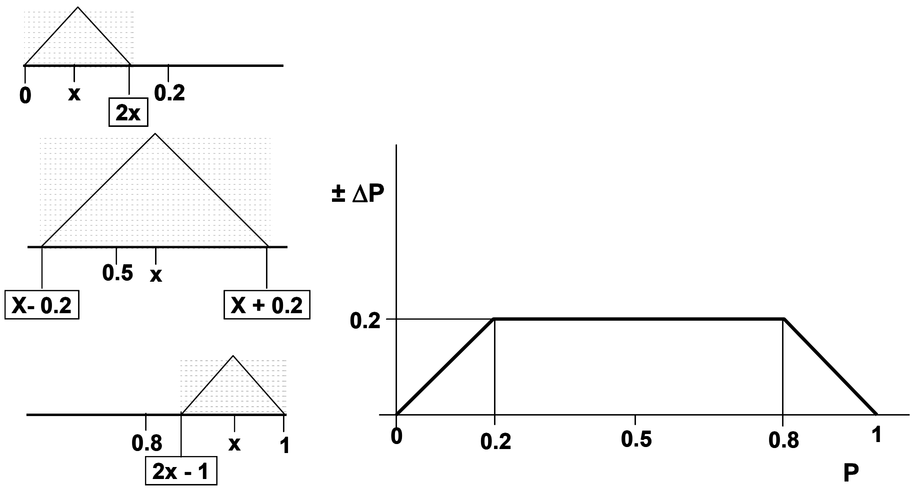


Figure 9 Assumed uncertainty in judgment of P values in event tree diagrams

5.4 Results of worker safety assessment

Results of the worker safety assessment are represented by the annual probability of fatality (APF) values derived from the event tree analysis using the annual personnel exposure data. The typical representation of results is indicated in Figure 10 where the APF have been plotted versus the year for two alternative mining plans, i.e. the base case as planned (shown as Ref plan) and the steepened case (shown as PND plan). The analysis was carried out on the estimated most representative sections of the slope. Results plotted correspond to values calculated with 50 and 90% confidence levels that they will not be exceeded. The curves show a distinct increase in risk toward the end of the life of the open-pit mine and suggested the need for some mitigation strategies.

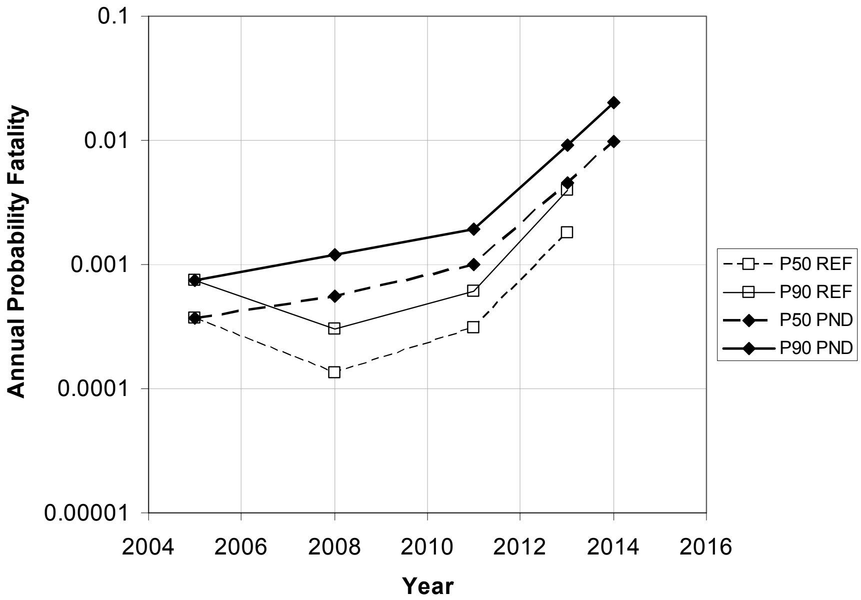


Figure 10 Typical results of safety evaluation for global failure on the west wall

Safety evaluations of the inter-ramp and bench slopes were also carried out. Conclusions from these potential failure modes are similar to those for the global analyses; with the suggestion of some mitigation measures required in particular areas. This is not unusual as the slopes have been designed to approach the limiting state of stability for economic reasons.

5.5 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 at the left on Figure 11 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 (HSE, (2001), 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.

The "local tolerability line" defines a region which is characterised 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.

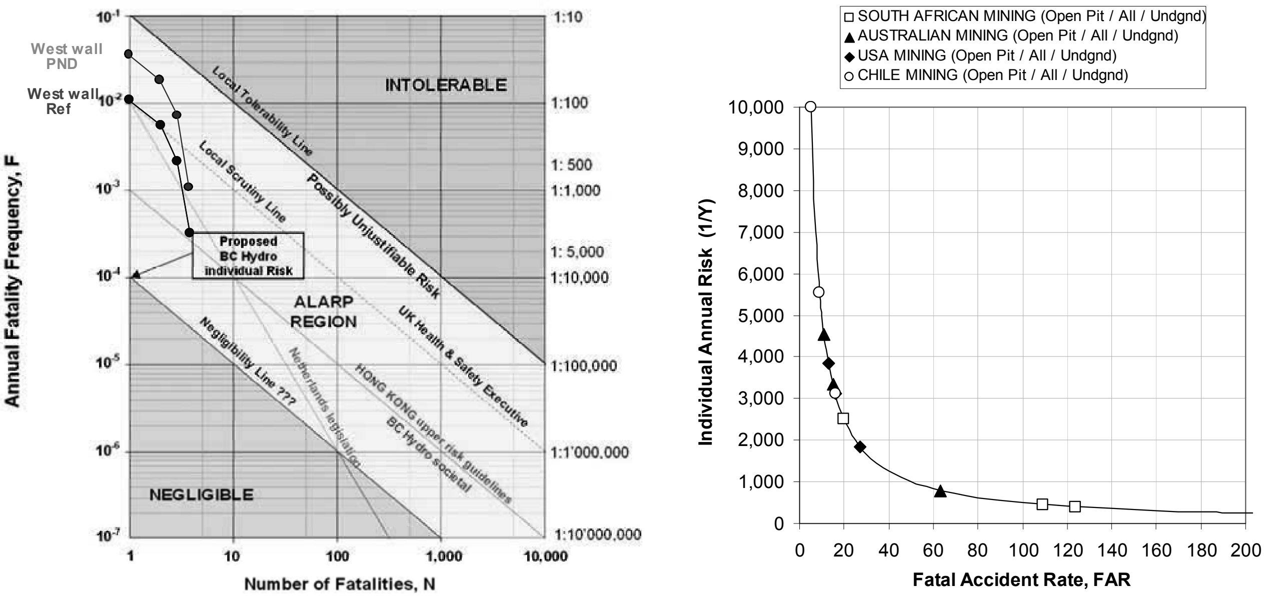


Figure 11 Benchmark criteria for safety impact of slope failure; acceptability criteria defined by different organisations (left) and statistics on fatal incidents in the mining sector (right)

The graph also contains fatality criteria developed by the dam engineering discipline, which are of interest as bench mark criteria, because they are 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 criterion 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 calculated annual probability of fatality (APF) for the final year of the plan at Chuquicamata falls within the ALARP region, which is a result consistent with the stage of development of the pit. The points plotted for more than one fatality in Figure 11 are the result of a collective fatality calculation based on assumptions of gang sizes exposed.

To help in the interpretation of the APF defined, 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 also be calculated from the FAR value. The information is presented in the form of a plot of FAR versus the annual individual risk at the right on Figure 11. 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.

6 Risk analysis of slope failure — economic impact

6.1 Objective

The objective of this task was the assessment of the consequences of pit slope failure in terms of economic losses associated with impact on equipment, contracts and force majeure events. This is done through the estimation of the probability of occurrence of these losses and their costs.

6.2 Consequence analysis for equipment impact

The consequence analysis for the assessment of impact of slope failures on equipment is very similar to that described for personnel safety impact. The event tree for this analysis contain similar questions to those used for the personnel safety analysis, and the same arguments given to support the inputs are applicable, but in this case the new values refer to impact on equipment rather than on workers. In general the values for equipment reflect the lesser mobility and more difficult successful evacuation of equipment as compared with personnel.

Impact on equipment is the first of three economic criteria from slope failures. From an economic scale perspective it is the smallest of the three and an event which is commonly encountered in the open pit mining arena, i.e. a first order cost. Typically the economic implications could imply an additional cost in the range of US$10 M to US$30 M in any one year. Economic impact is firstly the cost of repair or replacement of equipment and secondly the loss of production that may result. The latter is often the more important consequence and its analysis is described next.

6.3 Event tree analysis for economic impact of slope failures

Figure 12 shows the typical event tree developed for the evaluation of economic impact of slope failures. The components of the tree addressed the following questions:

- Is copper production affected?
- Can contracts be met?
- Are costs prohibitive?
- Can production be replaced by spot purchase?
- Are there additional costs?

The probability values assigned to the answers to this question are the reflection of aspects like: type of failure, expected volume of the slide, typical velocity of the failure, location of slide in relation to access ramps, availability of alternative ore sources and similar type of considerations.

The analysis enables the evaluation of the probabilities associated with each of the three possible consequences in terms of economic impact, i.e. force majeure event, loss of profit or minor impact represented by normal operating conditions.

6.4 Probability of loss of profit

The loss of profit is the second order of costs that could be incurred due to a slope failure, and would typically range from US$50 M to US$200 M. It is mainly associated with slope failure at inter-ramp and global scale.

A typical representation of results is presented in Figure 13 as trends with time for each of the mining plans evaluated. Results are reported in terms of annual probability of loss of profit for confidence levels of 50% (broken lines) and 90% (solid lines). There are no fixed criteria that can be assigned to this consequence as it is dependent on the client's appetite for risk balanced against the benefits accrued from the additional risks.

6.5 Probability of Force Majeure

Force majeure is the third order of economic impact evaluated and represents the event of a slope failure of such magnitude that copper production is severely affected or could lead to the premature closure of the open pit operations.

The possible occurrence of a Force Majeure (FM) situation was computed for various years at typical representative sections of each wall. Figure 14 presents a plot that integrates the results of probability of Force Majeure calculated for east and west walls and for global and inter-ramp scale failures, as this is an event impacting the overall pit. Figure 14 therefore represents the overall probability of a FM event within a plan from any slope failure. This figure also distinguishes the risk exposure to FM between the two plans. It clearly demonstrates the higher risk attached to the steepened case (PND) from that of the base case (Ref).

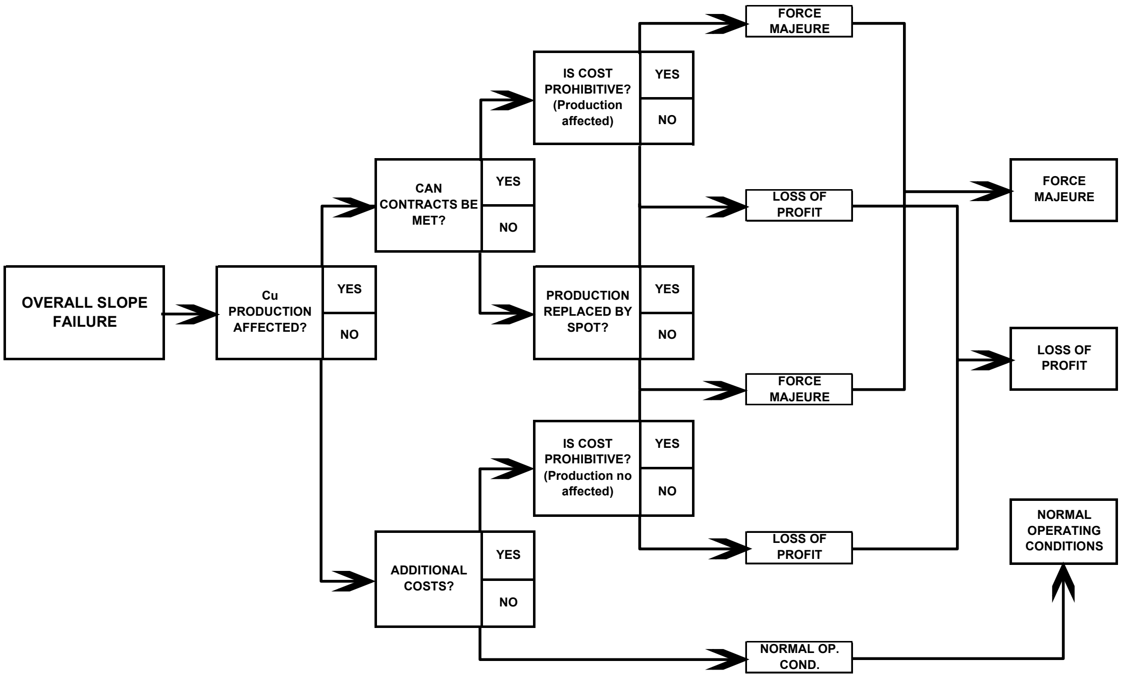


Figure 12 Event tree diagram for evaluation of big economic impact of slope failures

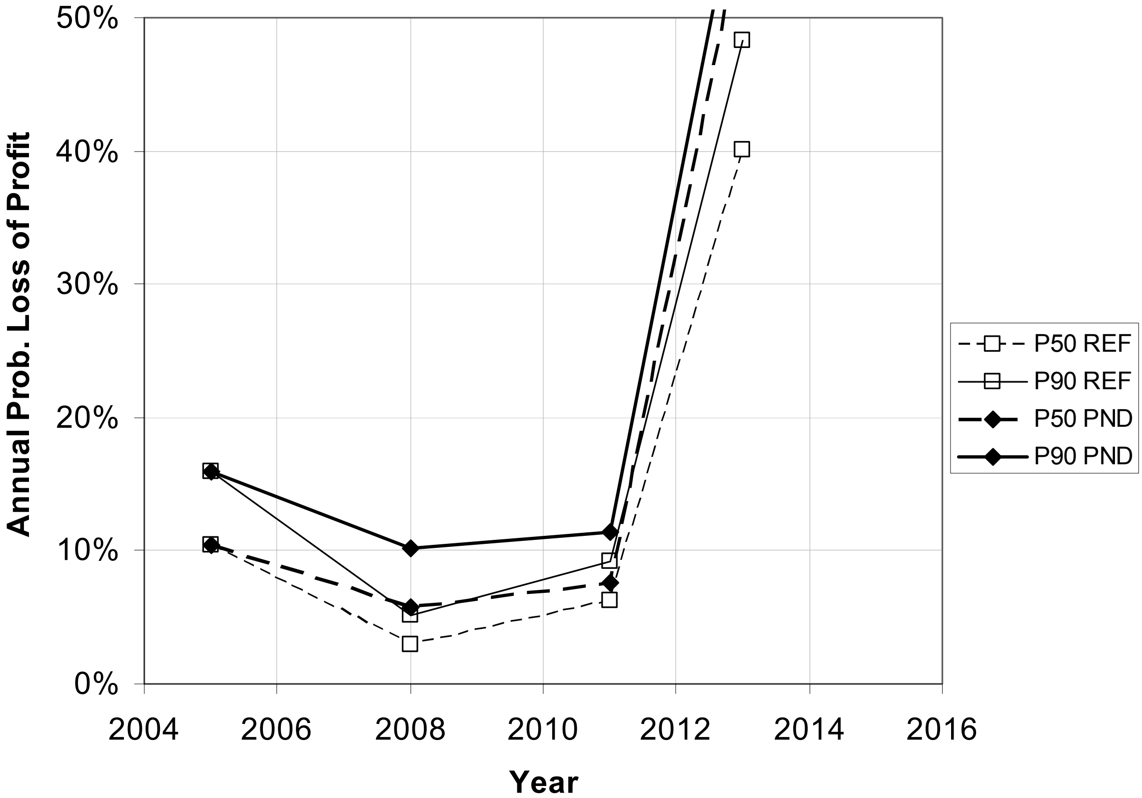


Figure 13 Typical results of loss of profit impact for global failure on the west wall

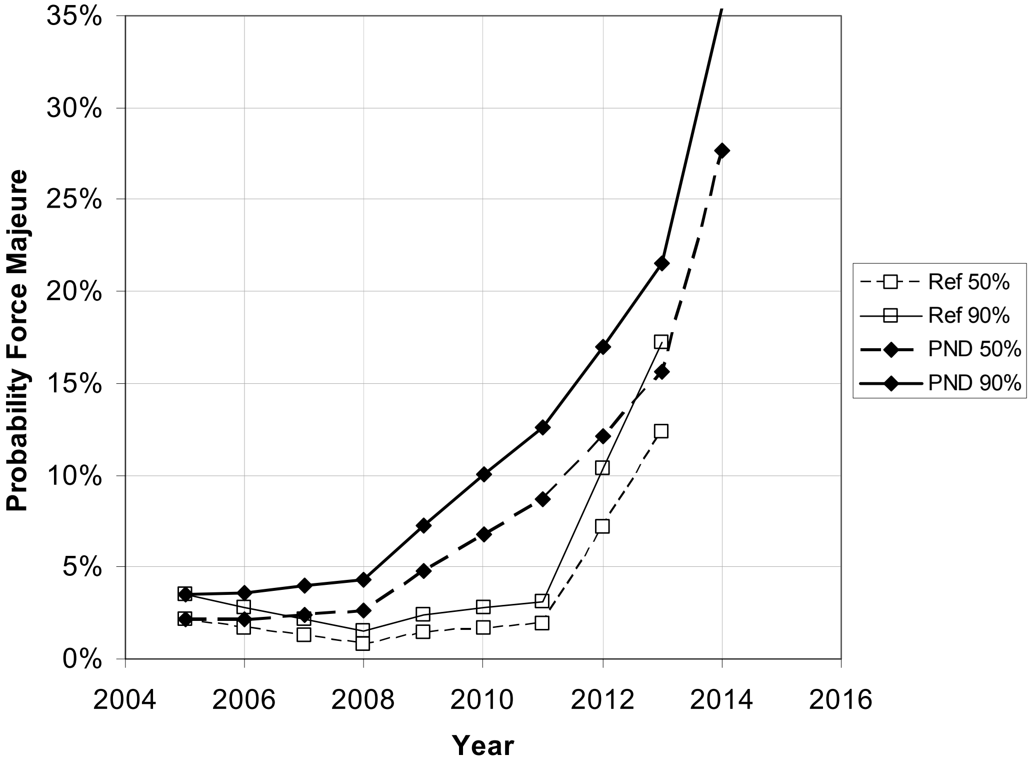


Figure 14 Exposure to force majeure for the two plans evaluated

6.6 Cost risk results

The results of probabilities of FM were then combined with the cash flow values of the two plans to produce graphs indicating the cost implications of the Force Majeure events. In the case of a Force Majeure event, the cost of failure equals the total loss of future NPV from the time of failure.

The curves in Figure 15 correspond to the cumulative discounted earnings and show the "actual indicated value" (thick lines), as declared in the project report, and the "including risk value" (thin lines), which for this study was defined as the 90% confidence value. The difference between these two lines for each plan corresponds to the "at risk value", which is defined as follows:

At risk value = Actual value (promised) - 90% confidence value

The actual values in this definition are based on the assumption that there is no risk of occurrence of the Force Majeure event. Technically, the curves for the situation with risk are developed from the probability of no failure occurring multiplied by the project NPV.

Quantifying the economic value of risk according to the definition of risk used in this report is a common practice in financial institutions and the insurance industry amongst others. However, the framework of the results is slightly different. Whereas in the financial industry situations incomes are derived from the premiums or interest rates charged based on the value assessed after including the 'cost of risk', in the case of a mine the issue is the expected cash return from the recovery of the ore. This is conveniently expressed as the net present value (NPV) with the effect of risk being reflected in the confidence that the forecast NPV will be achieved.

From a mining perspective, the lower NPV resulting from including the risk-cost calculated as shown above is not an achievable NPV within the particular mine plan in case of a Force Majeure event, but purely a perceived cost of the risk. Hence for a higher confidence (or lower uncertainty), the risk cost increases. This information therefore does not allow the decision process of trading additional benefit for increased risk. This would require alternative mine plans.

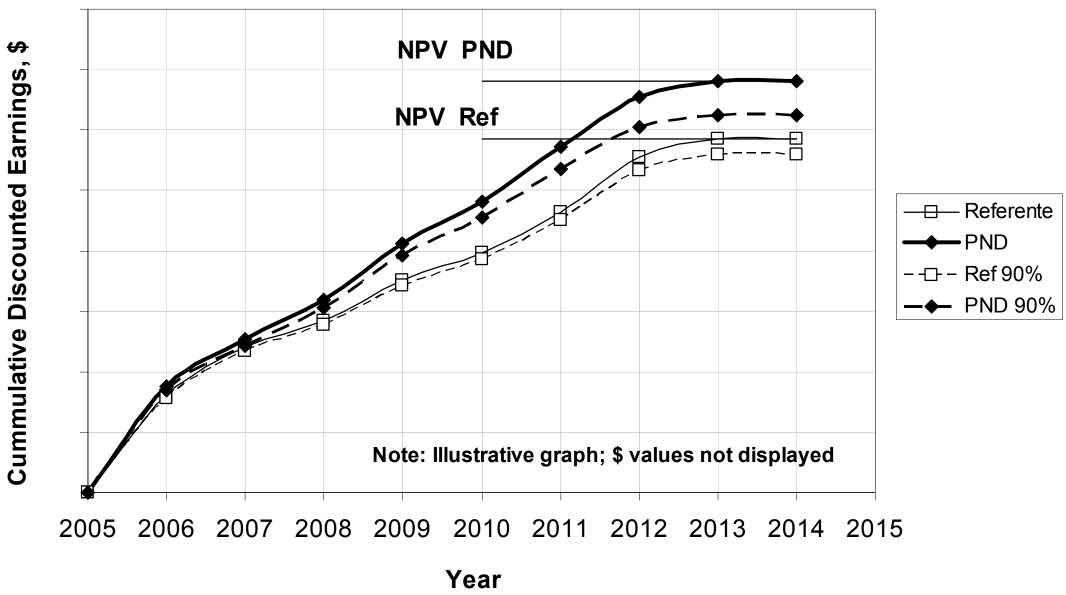


Figure 15 Cost impact of Force Majeure events

7 Analysis of mitigation measures

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 enables the identification of slope management improvements to have the solution that provides the maximum cost-benefit at the required acceptance criteria. 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 POF of the slope may be required. These options include unloading and/or dewatering of slopes.

7.1 Mitigation options for safety impact

In terms of worker safety and equipment impact primary options are aimed at reducing the effects of slope failure, which is done through improvement of slope management procedures. The implementation of an enhanced monitoring system (radar system, seismic methods, extensometers, TDR system, etc.) to provide early warning of failures in inaccessible slopes was evaluated by adjusting the appropriate values in the event trees.

Results indicated that when the enhanced monitoring system is introduced, there is no difficulty in reaching the target safety criteria.

7.2 Mitigation options for economic impact

Mitigation options have been evaluated to determine the cost of reducing the risk of economic impact should this be preferred by management. Mitigation options include geotechnical options aimed at reducing the probability of failure of the slopes and mine planning options that target the reduction of failure impacts by looking for alternatives to maintain the planned ore feed. The scope of the study included only the evaluation of the geotechnical options. They include unloading the slope by additional stripping and drainage of the slopes.

Results of this analysis enable the identification of those areas where depressurization and/or unloading of the slopes would be effective measures from a cost-benefit point of view.

8 Conclusions

The risk analysis process applied to the Chuquicamata mine has shown how the system can be applied to evaluate the consequences of failure in terms of personnel safety and economic impact. Also, the method has been useful in the definition of risk mitigation options pertaining to mine design procedures.

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

The evaluation of risk in terms of NPV at risk is a useful approach in comparing the performance of alternative mine plans. However, for the purpose of committing to a particular mine plan, the estimated likelihoods of particular consequences of all slope failures need to be adjudicated and assessed against an acceptable risk to the mining operation. This ultimately requires judgment using all the knowledge available as well as having a full understanding of all uncertainties.

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