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Geotechnical risk analysis for the closure alternatives of the Chuquicamata open pit

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Abstract

The development of the geotechnical risk model for the Chuquicamata mine started in 2005 and included the safety and economic impacts of slope failures at different scales (Tapia et al. 2007; Steffen et al. 2008). The model has been updated recently to include a quantitative evaluation of large economic impacts derived from inter-ramp and overall slope failures using a probabilistic approach (Contreras 2015). This paper describes how the later component of the model was used as a tool for the evaluation of four closure alternatives for the open pit. The methodology included three main tasks:

1. *Evaluation of the Probability of Failure (PF) representative of the stability conditions of pit slopes.*
2. *Evaluation of the consequences of slope failure associated with economic losses derived from impacts on production and costs.*
3. *Generation of risk maps to compare several closure alternatives.*

The results of these analyses provided information on magnitude of impacts and their likelihood for the four closure alternatives evaluated. The evaluation of these results facilitated the selection of the appropriate closure alternative considering the mine reference criteria for economic risk.

Keywords: *risk model, risk map, slope stability analysis, economic impact of slope failure.*

1 Introduction

The Chuquicamata copper mine is located in the northern part of Chile, about 16 km from the city of Calama. The mine has one the world's largest open pits (Figure 1) with a length of 4,500 m, a width of 2,700 m, and a depth of 950 m. Mining began in 1913 and the mine currently moves 600,000 t of material daily. The mine slopes have been aggressively steepened to optimise the mining business and therefore, the open pit has suffered several slope instabilities in the last 50 years, as shown in Figure 2.

The geotechnical risk model for the Chuquicamata mine was initially developed in 2005 and included the safety and economic impacts of slope failures at overall, inter-ramp and bench scales (Steffen 1997; Tapia et al. 2007; Steffen 2007; Steffen et al. 2008). The model was recently updated to include the quantitative evaluation of economic impacts from large-scale slope failures (Contreras 2015a).

The study described in this paper corresponds to the work carried out by the mine's geotechnical department during the years 2013 to 2016, with the support of SRK Consulting (Ortubia et al. 2013, 2016; Contreras 2015b), with the objective of providing the management with the appropriate information to base decisions on the best slope steepening alternative for closure of the pit. The base case mine plan considered for the risk study is named plan 'Plan de Negocios (PND) 2013', which contemplates production up to year 2019, when the mine will cease the surface mining giving way to the underground mine operation. The risk study focused on the assessment of four alternative slope configurations for closure of the open pit in terms of the potential economic impact from slope failure events.

The methodology included three main tasks:

1. Evaluation of the Probability of Failure (PF) representative of the stability conditions of pit slopes.
2. Evaluation of economic losses derived from impact on production and costs.
3. Generation of risk maps to compare the four closure alternatives.

The results of these analyses provided valuable information to assist the decisions on the closure plan in accordance with the mine's reference criteria for economic risk.

Figure 1 Panoramic view from the south of the Chuquicamata pit in 2014

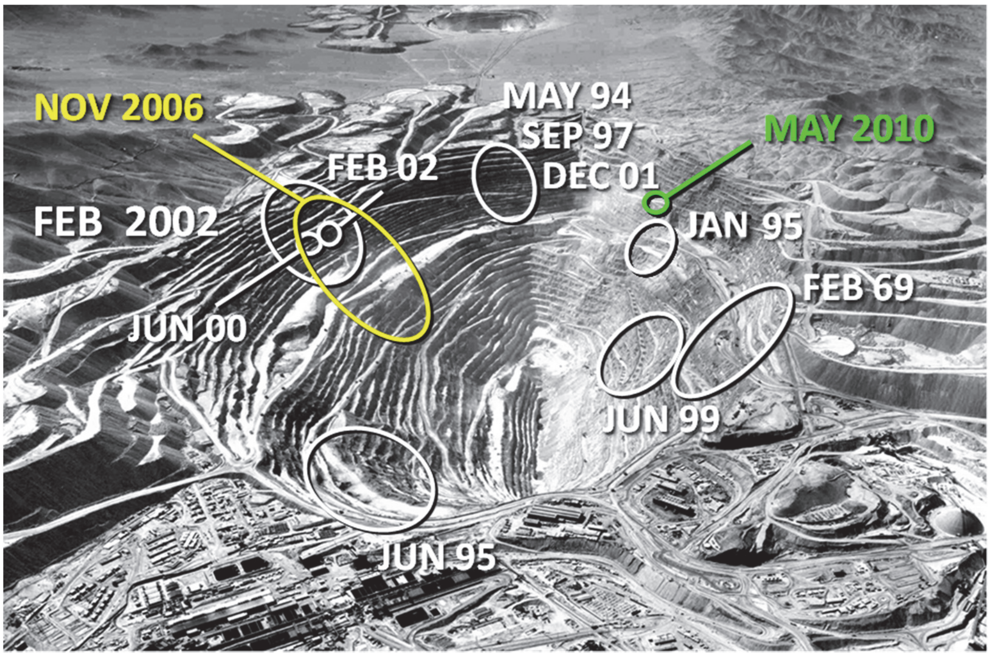


Figure 2 Panoramic view from the south of the Chuquicamata pit with slope instability events during the period 1968–2018 (adapted from Calderon et al. 2003)

2 The updated geotechnical risk model of the Chuquicamata open pit

The latest version of the risk model of the Chuquicamata pit was used for the analysis of alternative slope designs for mine closure. A thorough risk analysis of slope failure should include the assessment of impacts in terms of safety and economics. However, the study for the analysis of alternatives of closure focused on the economic impacts resulting from major failure events (inter-ramp and overall) in the pit. It was considered that the existing monitoring and warning systems covered adequately the safety risks associated with this type of events.

2.1 General considerations

The conventional methodology for the design of overall and inter-ramp pit slopes is based on the calculation of stability indexes, such as the Factor of Safety (FS) or the PF. The indexes are compared with acceptability criteria to define the appropriate slope angles, which are then used in the pit mining design (Steffen et al. 2008). An alternative design methodology is based on a quantitative assessment of the risks of slope failures, which are used as the objects to apply the acceptability criteria for slope design. The risks are typically calculated in terms of economic and safety impacts, however, the paper discusses only the economic risks. The diagram in Figure 3 (Contreras 2015a) shows the risk assessment process for slope design in terms of economic impact.

The main steps of the risk methodology described in this paper are:

1. Define a set of cross-sections for slope stability analysis to cover critical areas of the pit along the life-of-mine (LOM). The objective is to have a proper representation of the risks of slope failure for the mine plan evaluated.
2. Calculate the PF of the slopes from the stability analysis of the selected cross-sections.
3. Quantify the economic impacts of slope failure, referred to loss of annual profit or to project value as measured by the net present value (NPV).
4. Integrate the results of PF and economic impacts for the construction of economic risk maps per year and for the LOM.
5. Compare the risk map to the project specific reference criteria to produce an assessment of risk that is used in the decision-making process.

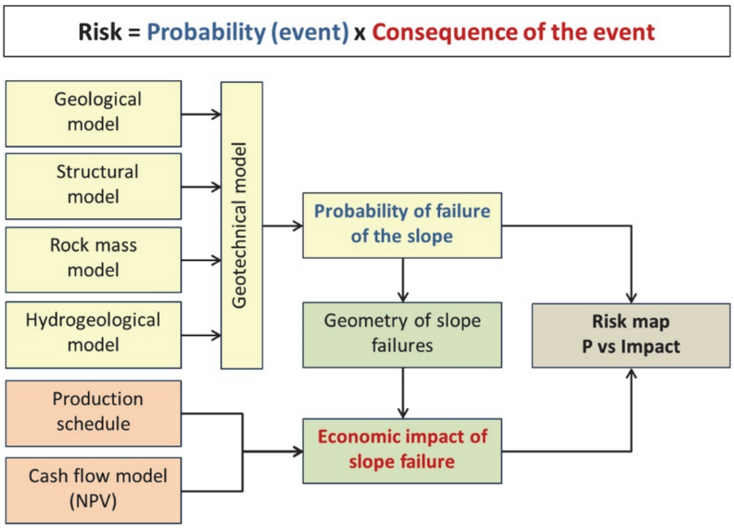


Figure 3 Risk-based slope design approach for economic impact (Contreras 2015a)

2.2 Slope stability analysis

The evaluation of the stability of the slopes included the following steps:

1. Assessment of forty cases of slope stability corresponding to the critical situations identified after the evaluation of expected conditions for the six years of the PND 2013 mine plan. The analysis considers the seven cross-sections shown in Figure 4. The plan of stability analyses is summarised in Table 1.

2. Evaluation of hydrogeological conditions to forecast pore pressure distributions in mine pit slopes. The analysis is based on a calibrated hydrogeological model for each section, incorporating the distribution of hydrogeological units, structures, and pit topography for different years, as well as drainage measures, and monitoring points.

3. The first stage of the stability analysis included bi-dimensional numerical models, using the Universal Distinct Element Code (UDEC) software (Itasca 2013) to allow for a better representation of the geomechanical characteristics of the materials. The task corresponded to back-analysis of observed slope performance and the analyses were used for the tuning of rock mass properties and the verification of failure mechanisms. The analysis included the instability of November 2006 with cross-section P5 for the west wall (see Figures 5 and 6) and the instability of May 2010 with cross-section P7A for the east wall (see Figures 7 and 8).

4. The second stage of the stability analysis consisted of finite element models with the program Phase2 (Rocscience 2010) intended to calibrate the UDEC models. Phase2 models require less process time and were used for the calculation of the PF. These analyses were carried out for all the sections and years included in Table 1 and the FS was determined with the shear strength reduction technique. Therefore, in this study, the FS values really correspond to strength reduction factors (SRF).

5. Once the tuning analyses were completed and the results of the stability evaluations indicated similar SRF values with the UDEC and Phase2 models, the probabilities of failure were determined with the response surface (RS) methodology (Steffen et al. 2008) using the Phase2 slope models.

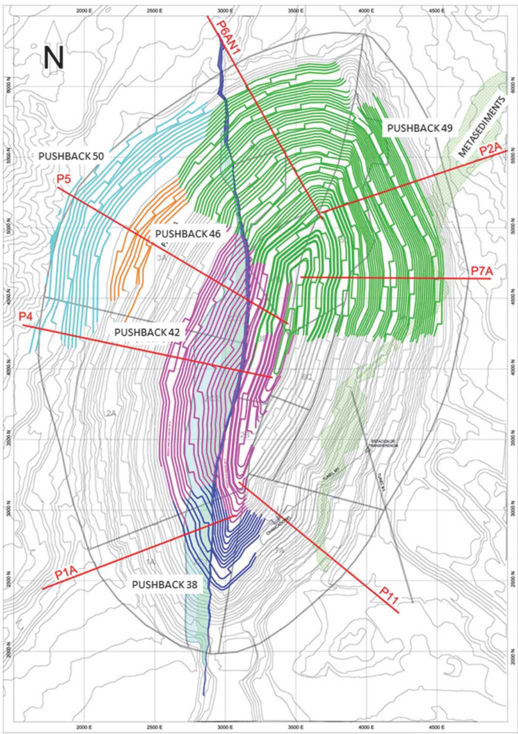


Figure 4 Plan view with the location of geotechnical cross-sections and pushbacks according to the PND 2013 plan

Table 1 Geotechnical cross-sections for the slope stability analysis of plan PND 2013

Year	Ore								Waste
	Pushback 42					Pushback 49			Pushback 50
2014		P4	P5	P7A	P11	P2A	P6AN1	P7A	P5
2015	P1A	P4	P5	P7A	P11	P2A	P6AN1	P7A	P5
2016		P4	P5	P7A	P11	P2A	P6AN1	P7A	P5
2017		P4	P5	P7A	P11	P2A	P6AN1	P7A	
2018					P11	P2A	P6AN1	P7A	
2019					P11	P2A	P6AN1	P7A	

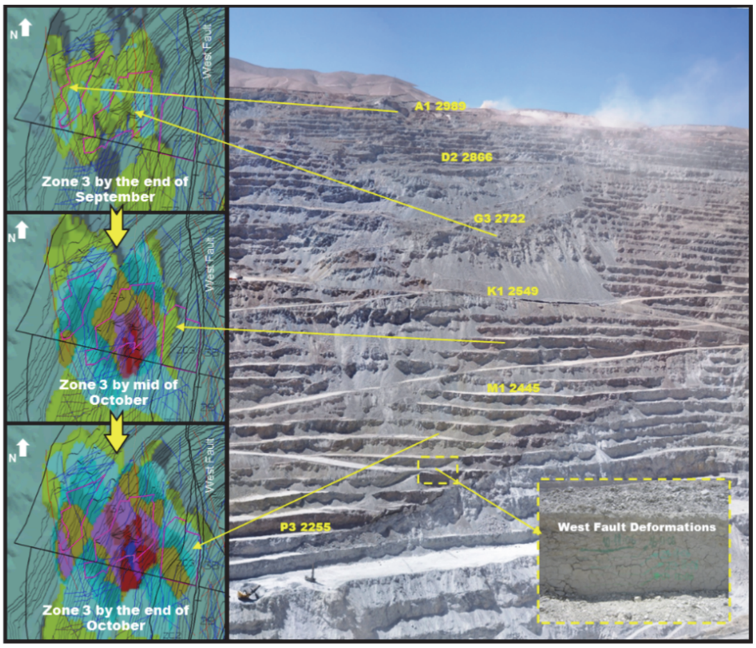
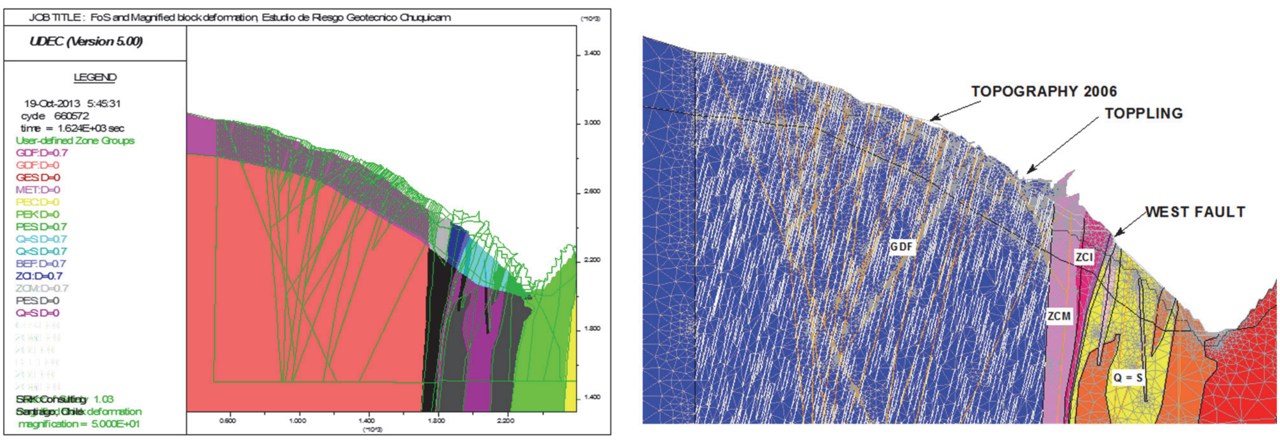


Figure 5 Evolution of total displacements recorded for the instability of November 2006 in the geotechnical zone 3 of the Chuquicamata west wall (Ledezma 2013)



(a) (b)

Figure 6 Results of the back-analysis of the instability of 2006. (a) Results from the UDEC model with a FS = 1.03; (b) Results from the Phase2 (Rocscience 2010) model with a FS = 1.03. The mesh is purposely exaggerated in these graphs to show the failure mechanism

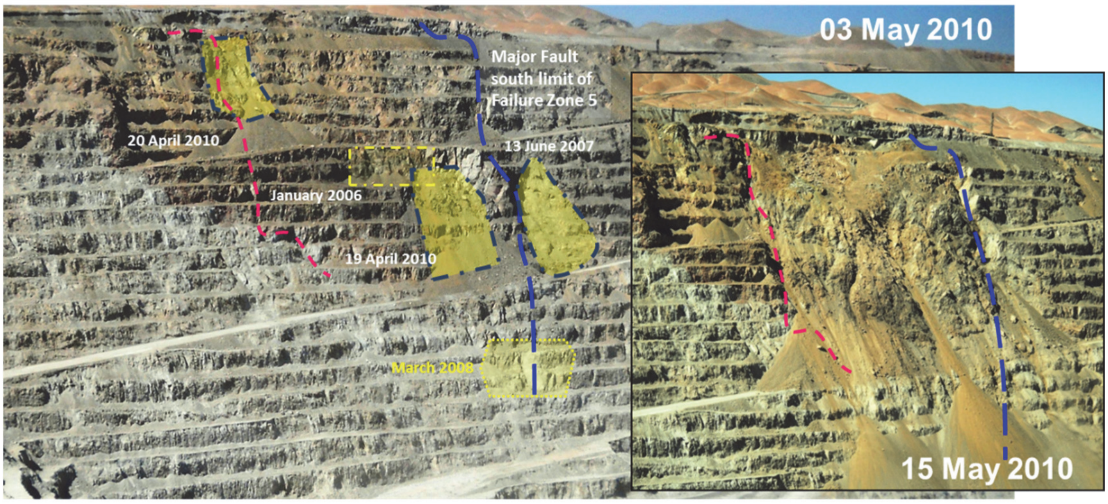
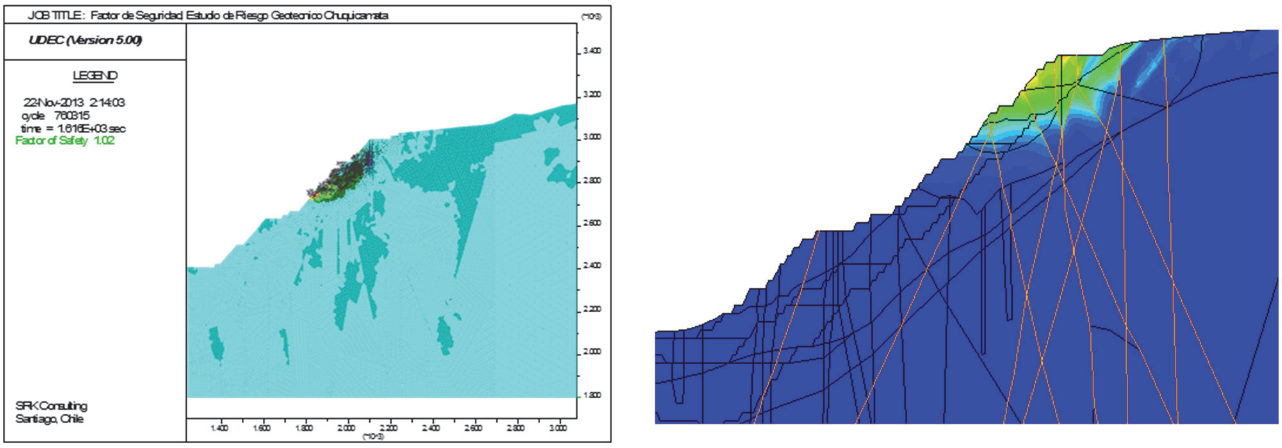


Figure 7 Evolution of the instability of May 2010 observed in the geotechnical zone 5 of the Chuquicamata east wall (Ledezma 2014)



(a) (b)

Figure 8 Results of the back-analysis of the instability of 2010. (a) Results from the UDEC model with a FS = 1.02; (b) Results from the Phase2 (Rocscience 2010) model with a FS = 0.98

2.3 Probability of Failure of the slopes

The PF of the slopes for the risk evaluation is based on a Monte Carlo analysis, using a surrogate slope model expressed in polynomial form constructed with the RS methodology. The RS is generated from the SRF values calculated with the slope numerical model using the base and extreme cases of the input parameters considered as uncertain variables. Steffen et al. (2008) describe the RS methodology in detail. There is no distinction between overall and inter-ramp slopes for the calculation of the PF of the slopes, as the scale of the failure is determined by the failure mechanism resulting from the geomechanical analysis. The PF from the analysis of each section is used in the economic impact analysis.

In general, the PF calculated with the numerical models only considers the uncertainties of the strength properties of the geotechnical units and is referred to as PF_{model}. In the present study, the uncertainties included in the calculation of PF_{model} are the variability of the uniaxial compressive strength and geological strength index of each geotechnical unit; the strength of the ubiquitous discontinuities in the Granodiorita Fortuna unit; and the strength of major faults.

The model uncertainty is represented by the critical FS ($FS_{critical}$) that defines the failure condition with the numerical model used for the slope stability analysis. The Chuquicamata risk model considers $FS_{critical}$ = 1.0, with variability between 0.95 and 1.05. These values are supported by the results of the tuning analyses with the software UDEC and Phase2.

Uncertainties due to other factors are incorporated into the model by the calculation of their contribution to the PF_{total} required for the consequence analysis. The calculation is based on Equation 1:

$$PF_{total} = 1 - (1 - PF_{model}) \times (1 - PF_{quake}) \times (1 - PF_{water}) \times (1 - PF_{geology}) \quad (1)$$

where:

PF_{quake} = probability of slope failure due to occurrence of seismic events of large magnitude.

PF_{water} = probability of slope failure due to occurrence of abnormal water conditions.

$PF_{geology}$ = probability of slope failure due to occurrence of adverse geological conditions.

PF_{model} = probability of slope failure due to uncertainties included in the analysis with numerical models.

In the case of seismic conditions, PF_{quake} is based on the annual probability of occurrence of the maximum credible earthquake (MCE) which has a return period of 10% in 100 years. The contribution due to the seismic event assumes a PF of the slope of 50% during the MCE.

The PF_{water} is based on the assumption of a probability of occurrence of abnormal unfavourable water conditions of 2% in the west wall and 1% in the east wall, during the years of the mine plan. Likewise, the $PF_{geology}$ is based on probabilities of occurrence of abnormal conditions of 10, 15 and 20% for the west, north, and east walls, respectively, during the six-year plan. These conditions refer to the width of the shear unit in the west wall, the occurrence of major structures in the north wall, and to uncertainties in the characterisation of the metasediments unit in the east wall. The assumptions for the estimation of the uncertainties associated with abnormal groundwater and geological conditions are based on expert knowledge derived from consultation with the hydrogeology and geotechnical teams of the mine. Table 2 shows a summary of the results of the PF_{total} used in the risk model.

Table 2 Summary of PF_{total} results for plan PND 2013

Section	Year of life-of-mine					
	2014	2015	2016	2017	2018	2019
P1A	48.3%	33.9%	34.0%	34.1%	34.1%	34.2%
P4	58.0%	55.7%	57.9%	68.4%	68.8%	69.2%
P5	1.3%	3.2%	1.5%	1.9%	2.1%	6.6%
P6A1N	1.2%	1.2%	1.3%	1.4%	1.5%	1.6%
P2A	1.4%	1.5%	5.2%	90.3%	11.6%	12.2%
P7A	1.9%	1.3%	1.4%	9.3%	1.8%	1.7%
P11	1.2%	1.2%	1.3%	1.4%	1.5%	1.6%

2.4 Economic impact of slope failures

The measure of value of a mining plan is usually represented by the NPV. The NPV is normally the result of an optimisation process of the mine plan carried out with specialised software in order to maximise the economic benefits. In general, the economic impact of a slope failure event is derived from the disruption of the scheduled ore feed to the plant during the time required to restore the site, and from the additional costs caused by these activities. The economic impact of the slope failure is calculated as the difference between the NPV of reference (i.e. mine plan without slope failures) and the NPV considering the effects of the failure.

Production disruption may be caused by different factors such as interruption of access to the mining faces, ore coverage, and grade variations resulting from the use of alternative ore sources to mitigate the effects of the failure. Additional costs are caused by the re-handling of materials and re-scheduling of equipment during the time of implementation of the remedial actions.

2.4.1 Estimation of size of failures

The first step for estimating the economic impact of slope failure consists on quantifying the size of the spillage, which is directly related to the expected magnitude of the impact on production and costs. The estimation of the spillage volume is based on defining the geometry that best represents the failed mass. The estimation considers the results of a tri-dimensional geomechanical analysis, if they are available, and the knowledge on failure mechanisms and structural controls specific to the slope evaluated. However, the use of a simple geometrical criterion applied to the area of the failure derived from the bi-dimensional stability analysis is sufficient to estimate the relative effect of failures in different sections.

The failure clean-up volume corresponds to a fraction of the spillage volume for large-scale failures of overall and inter-ramp slopes. For the Chuquicamata case, the failure clean-up volumes were estimated assuming that they correspond to 10 and 20% of the total spillage for sections to the west and east of the west fault, respectively. For Section 11, it was considered that the total spillage would be removed due to its moderate size. These assumptions were based on expert judgement from the Chuquicamata geotechnical team. Figure 9 shows a comparison between the failure clean-up tonnages and the ore tonnages from the mining plan. This graph is useful to have a first indication of the expected impacts of slope failures on production.

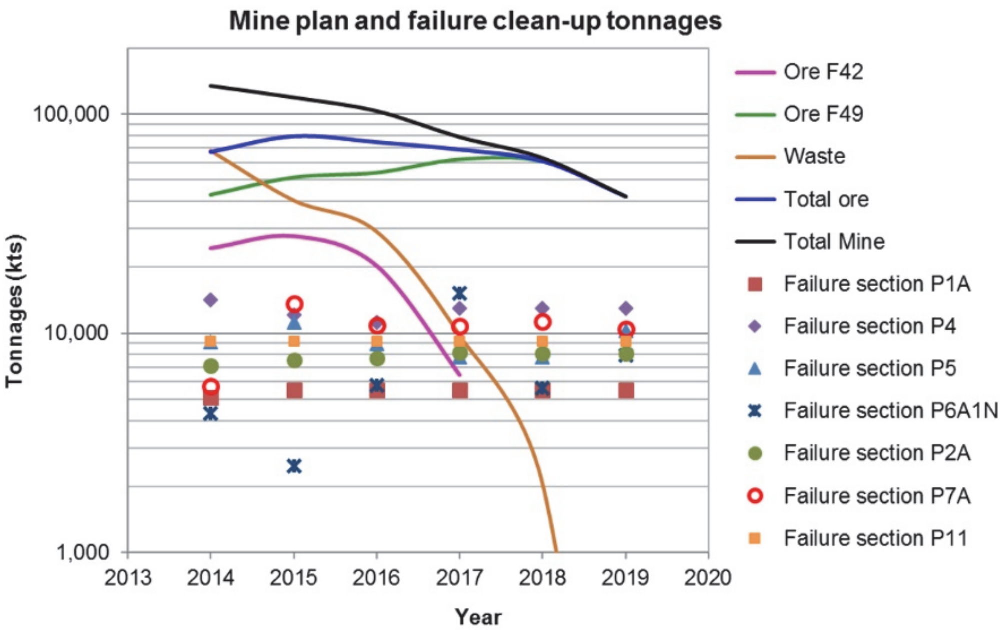


Figure 9 Comparison between failure clean-up tonnages and mining tonnages

2.4.2 Estimation of economic impacts

The estimation of the economic impact of slope failures in the Chuquicamata pit depends on the mechanism of failure. It is necessary to differentiate the case of failure where there is a spillage that needs to be cleaned up (east wall slopes), from the case of failure by excessive deformation that needs to be controlled to avoid an impact on production (west wall slopes). The descriptions of these cases are presented below.

2.4.2.1 Failure due to collapse with spillage (east wall)

In this case, the economic impact of the slope failure is calculated as the NPV reduction caused by the disruption of original feeding plan to the plant during the time required to restore the impacted site, and the additional costs caused by these activities. An approximate estimation of this impact is based on a simplified cash flow analysis (Contreras 2015a).

The impact corresponds to the reduction of the NPV caused by removing from production the tonnage of the affected pushback in the year of the failure event, during an estimated time according to the magnitude of the event. The magnitude of impact is expressed as a percentage of impact in production. The cash flow analysis considers the production, costs and investments components per pushback. The reduction of production causes an income reduction, which added to the additional costs, results in a reduced profit in the year of occurrence of the event and consequently in a reduced NPV. The failure impact corresponds to the difference between the reference NPV and the NPV considering the failure.

A disadvantage of the simplified cash flow analysis is that the more complex effects of a slope failure cannot be represented adequately with this method. These effects are related to grade variations occurring as a result of the use of stocks or alternative ore sources to mitigate the impact of the failure. For this reason, the estimated impact should be validated with the results from comprehensive assessments of selected events, similar to the assessment that would be carried out in an actual failure situation.

2.4.2.2 Failure by excessive deformation rate (west wall)

The failure mechanism of the slopes in the west wall corresponds to the increase of the deformation rate, exceeding admissible limits defined according to historic performance of the wall. The speed of deformation of the wall is controlled by unloading the slopes and therefore, the cost of the unloading works not included in the original mine plan is considered the economic impact of the slope failure.

The redesign of pushback 50 in the PND 2015 plan, to control the excessive deformation in the area covered by sections P4 and P5, considered the additional excavation of 56 Mt in four years, with an approximated cost of USD 200 million. This information was used as the reference to define a cost of USD 50 million per section and per year for the control of the rate of deformation. This value was used as the economic impact of slope failure for sections 4 and 5 for the scenario of west wall with unloading.

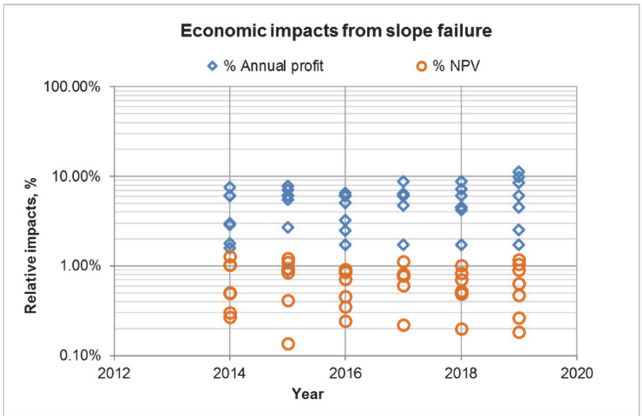
2.4.3 Results of the economic impact analysis

The estimation of production impacts has a component of expert judgement, but the impact factors need to be supported by reference calculations in order to capture the relative effect of the different failure events analysed. The first step is to define the productive pushbacks affected by the slope failure in the sections analysed, as shown in Table 3. Some events would not have impact on productive pushbacks, but in these cases, the impact would be reflected in the additional costs to restore the site. The impact factors included in Table 3 have been calculated considering a maximum impact equivalent to the loss of three months of production (impact factor = 3/12 = 0.25) when the clean-up tonnage is equal to the planned ore tonnage. Thus, the production impact factors in Table 3 correspond to one fourth of the clean-up tonnage normalised by the planned ore tonnage of the pushback affected (Figure 9). For example, it is estimated that the failure in section 2A in 2016 would affect 4% of the planned production of pushback F49.

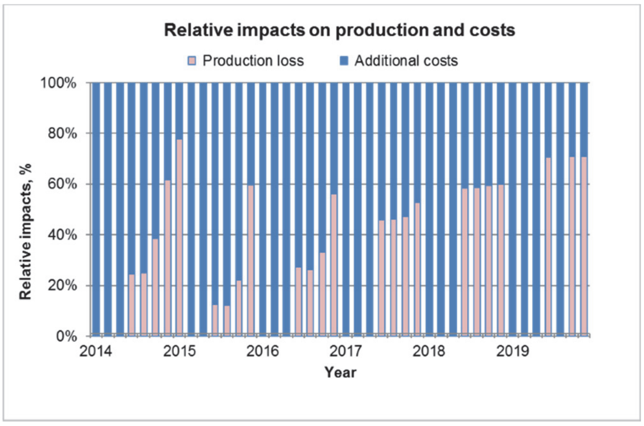
The results of the economic impacts, using a simplified cash flow analysis are shown in Figure 10, including impacts on NPV and annual profits. In general, the results suggest that the contribution of the additional costs component to the total impact is higher than 50%. However, these results should be interpreted with caution due to the various assumptions made during the estimation process.

Table 3 Impact factors of slope failure on productive pushbacks

Section	Year of life-of-mine					
	2014	2015	2016	2017	2018	2019
P1A		F42/5%				
P4	F42/15%	F42/11%	F42/4%	F42/25%		
P5	F42/9%	F42/10%	F42/11%	F42/25%		F49/6%
P6A1N	F49/3%	F49/1%	F49/3%	F49/6%	F49/2%	F49/5%
P2A	F49/4%	F49/4%	F49/4%	F49/3%	F49/3%	
P7A	F49/3%	F49/7%	F49/5%	F49/4%	F49/5%	F49/6%
P11	F42/3%	F42/3%	F42/3%	F42/3%		



(a)



(b)

Figure 10 (a) Economic impacts from slope failure; (b) Relative contribution to impact from production loss and additional costs

The results in Figure 10 suggest that the impacts on annual profits have a steady moderate increase up to the end of the LOM, while the impacts on NPV are more or less constant in time. In general, the impacts on NPV are less than 1% of the reference NPV, whereas the impacts on annual profits vary from 2–10% of the respective annual profit.

2.5 Economic risk map

The integration of the results of PF and economic impact described in the previous sections are used to construct risk maps per year and for the LOM. The risk maps facilitate the comparison of the results of the risk analysis with specific reference criteria defined for the Chuquicamata pit. The risk map describes the relationship between the probability of having a given economic impact and the magnitude of that impact. The construction of the risk map considers multiple possible situations of events occurrences in a year. Contreras (2015a) describes in detail the basis of the methodology.

The risk map results for the PND 2013 mine plan considering the unloading of the west wall are shown in Figure 11. These results are based on the PF and impacts on NPV described in Sections 2.3 and 2.4, respectively. These graphs show the relationship between the probability of exceeding the impact on NPV and the magnitude of the impact. The blue dots in the graphs correspond to the occurrence of isolated failure events, the green dots to the occurrence of several events and the red dot on the horizontal axis corresponds to the specific situation of no occurrence of any failure event. The envelopes correspond to the cumulative probability distribution curves of all the possible combinations of events and define the economic risk profile in terms of slope failure of the respective year.

The inclusion of individual events in the risk graphs for each year is useful for identifying the critical events that increase the risk level measured by the envelope. An example of this situation is shown in the graphs for years 2015 and 2017 of Figure 11, where potential instabilities in sections P1A, P4 and P2A are responsible for the increase of risk indicated by the envelope.

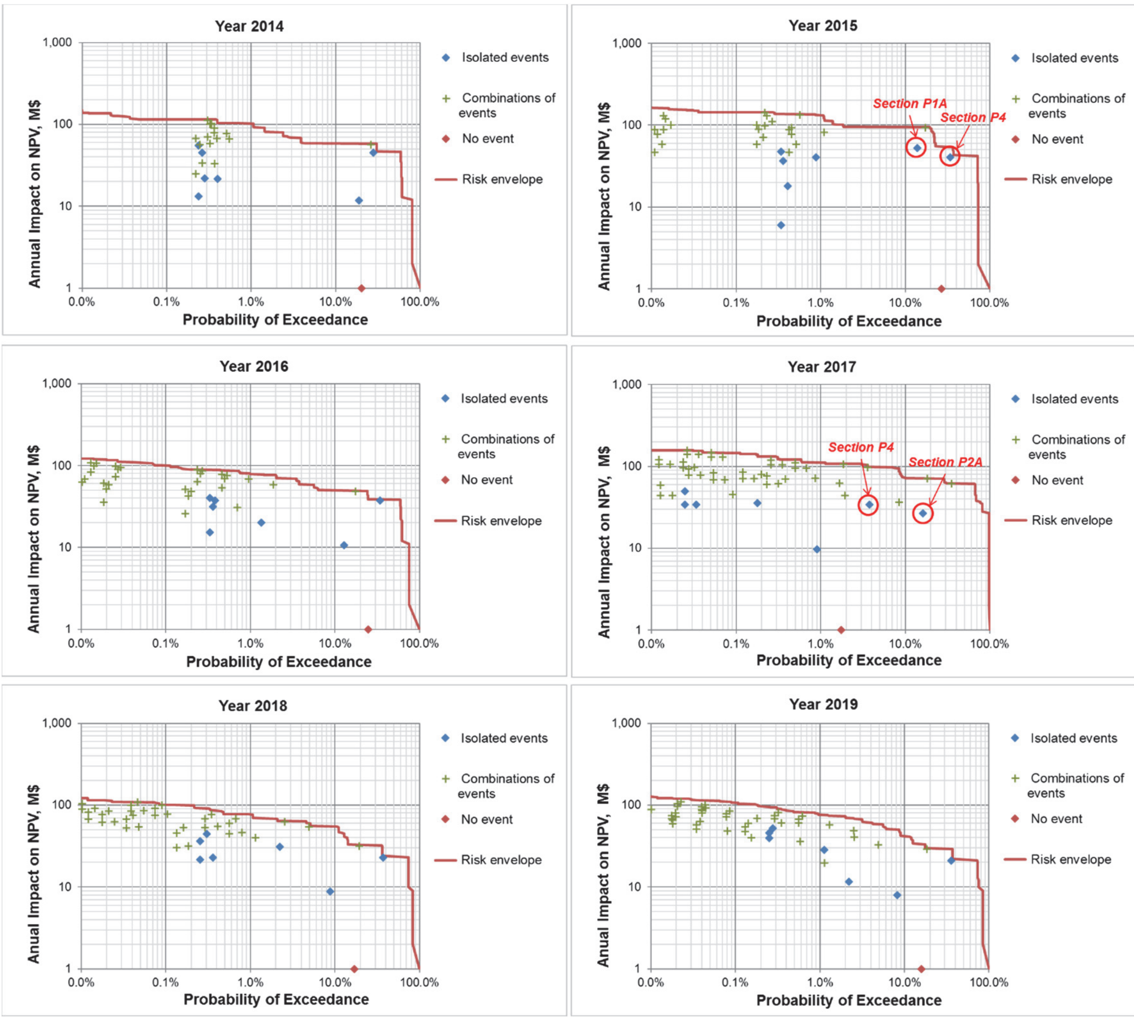


Figure 11 Economic risk envelopes of analysed years. The graphs indicate the exceedance probability in the horizontal axis and the annual impact on NPV in the vertical axis

The complete economic risk map is show in Figure 12. This graph groups the risk envelopes for each year of the mine plan, as well as the envelope indicating the cumulative risk for the LOM. The procedure to define the LOM risk envelope is based on adding the probabilities from different years for specific impact values, using the concept of system reliability (Harr 1996). The probability of an annual economic impact during the LOM (P_{LOM}) in Figure 12 is calculated using Equation 2:

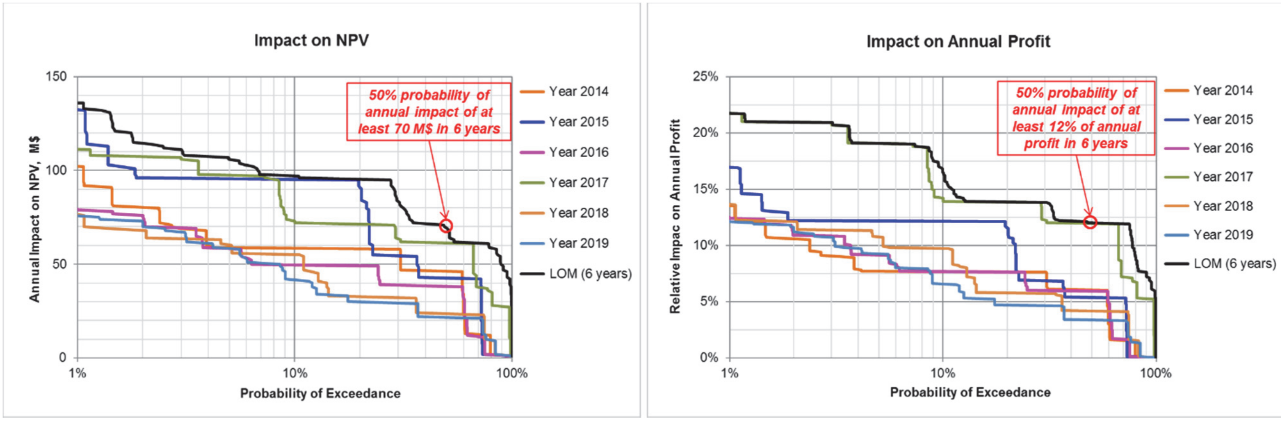
$$P_{LOM} = 1 - (1-P_{2014}) \times (1-P_{2015}) \times (1-P_{2016}) \times (1-P_{2017}) \times (1-P_{2018}) \times (1-P_{2019}) \quad (2)$$

where:

P_{year} = annual probability of economic impact in indicated year.

The interpretation of the economic risk envelope for the LOM in terms of impact on NPV is shown in the graph at the top of Figure 12, where the pointed value corresponds to the 50% probability of having an impact of at least USD 70 million during the six years of the mining plan. This graph is useful to identify the most relevant years and areas of the pit in terms of potential economic impacts and to assess mitigation strategies to reduce risks.

The economic risk map can also be constructed in terms of impacts on annual profits. In this case, future monetary amounts are not discounted to present values, which offers a different perspective of the impacts. The risk map for impact on annual profits is shown in the graph at the bottom of Figure 12, and its interpretation is illustrated with the pointed value indicating a 50% probability of an annual impact of at least 12% of the annual profit during the six years of mining. The result is presented in terms of relative impacts on annual profit to enable the integration of the curves for all the years in an envelope for the LOM.



(a) (b)

Figure 12 (a) Economic risk map for impact on NPV; (b) Economic risk map for impact on annual profit

3 Economic risk of mine closure alternatives

The risk evaluation carried out for the PND 2013 mine plan, as described in Section 2, was updated to include the stability assessment of the slopes located in the northeast area of the Chuquicamata pit, according to the PND 2015 mine plan. This area corresponds to the development of the pushback 49, as shown in Figure 13 with the geotechnical sections used for the analysis. The scope of the risk evaluation of this mine plan was extended to compare four closure options of the pit.

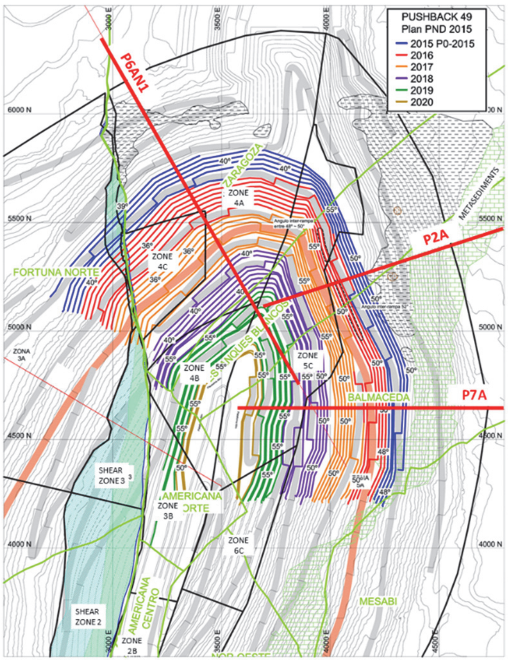


Figure 13 Location of analysed geotechnical sections according to the PND 2015 mine plan

The four closure options are associated with different configurations of the slopes as follows:

1. Base case slopes according to the PND 2015 mine plan.
2. Base case and a 25 m wide ramp below elevation 2,400 m.
3. Base case and a 3° steepening of the inter-ramp angle from the bench at elevation 2,497 m.
4. Base case and quadruple 18 m high benches (i.e. bench height = 72 m).

Figure 14 shows the main characteristics of the four slope configurations and includes the NPV of each option relative to the NPV of the base case configuration. The main differences between the options are in the lower part of the slopes and they correspond to the mining taking place during the final years of the mine plan.

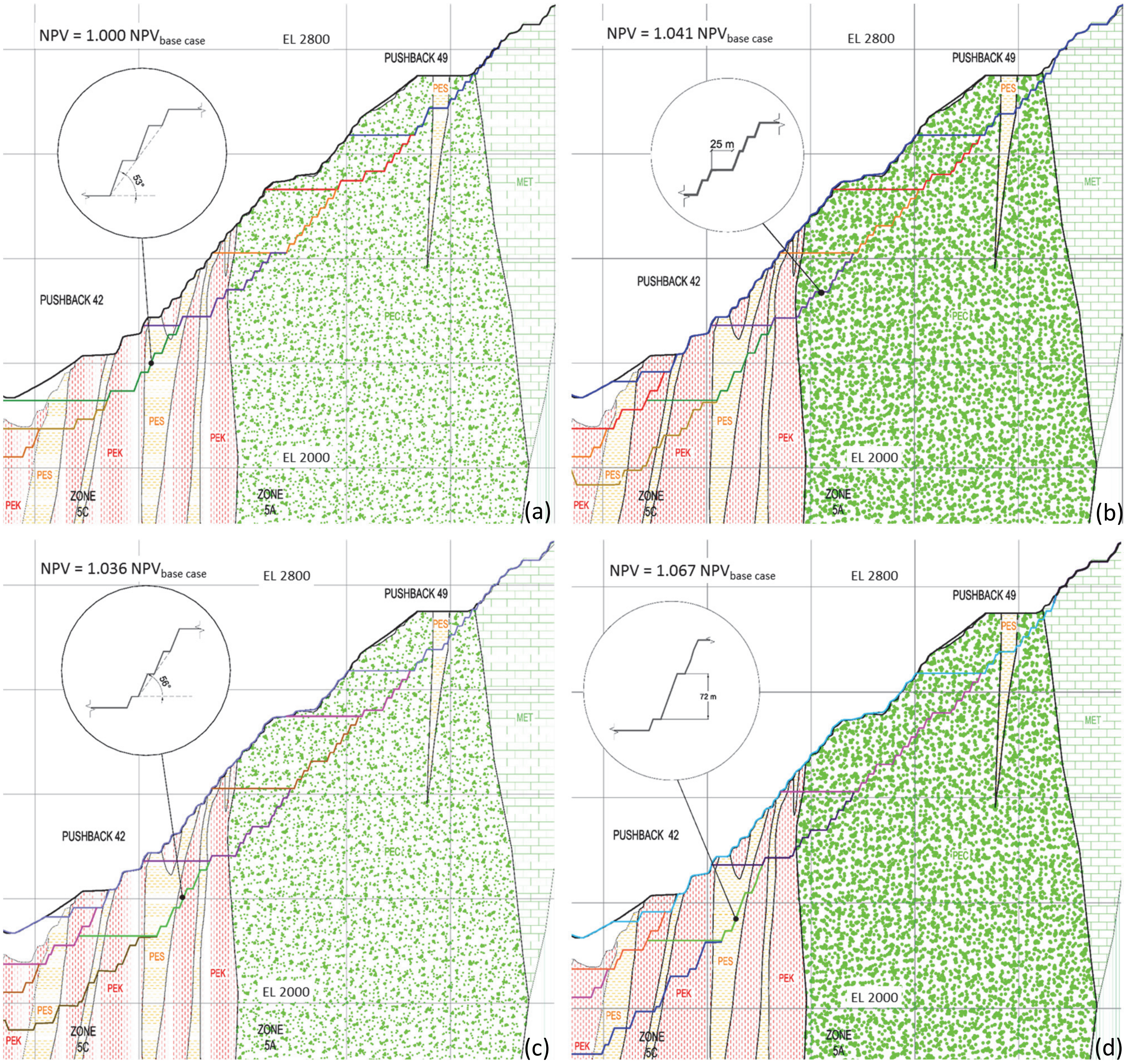


Figure 14 Slope configurations of the four closure options evaluated. (a) Base case; (b) Base case and a 25 m ramp; (c) Base case and 3° steepening of inter-ramp angle; (d) Base case and quadruple 18 m high benches

The economic risk maps in terms of impacts on the NPV for the four closure options studied are shown in Figure 15. The graphs include the risk envelopes for the individual years of the mine plan, as well as the risk envelope representing the situation for the LOM. There are no significant differences between the graphs in

Figure 15 because in this case, the risk maps are not sensitive enough to the differences between the four options, which are reflected in different probabilities of failure towards the end of the mine life. The NPV corresponds to the cumulative annual profits discounted to present value and therefore, the slope failures on the final years have a less significant effect on project value because a great proportion of the NPV already has been realised.

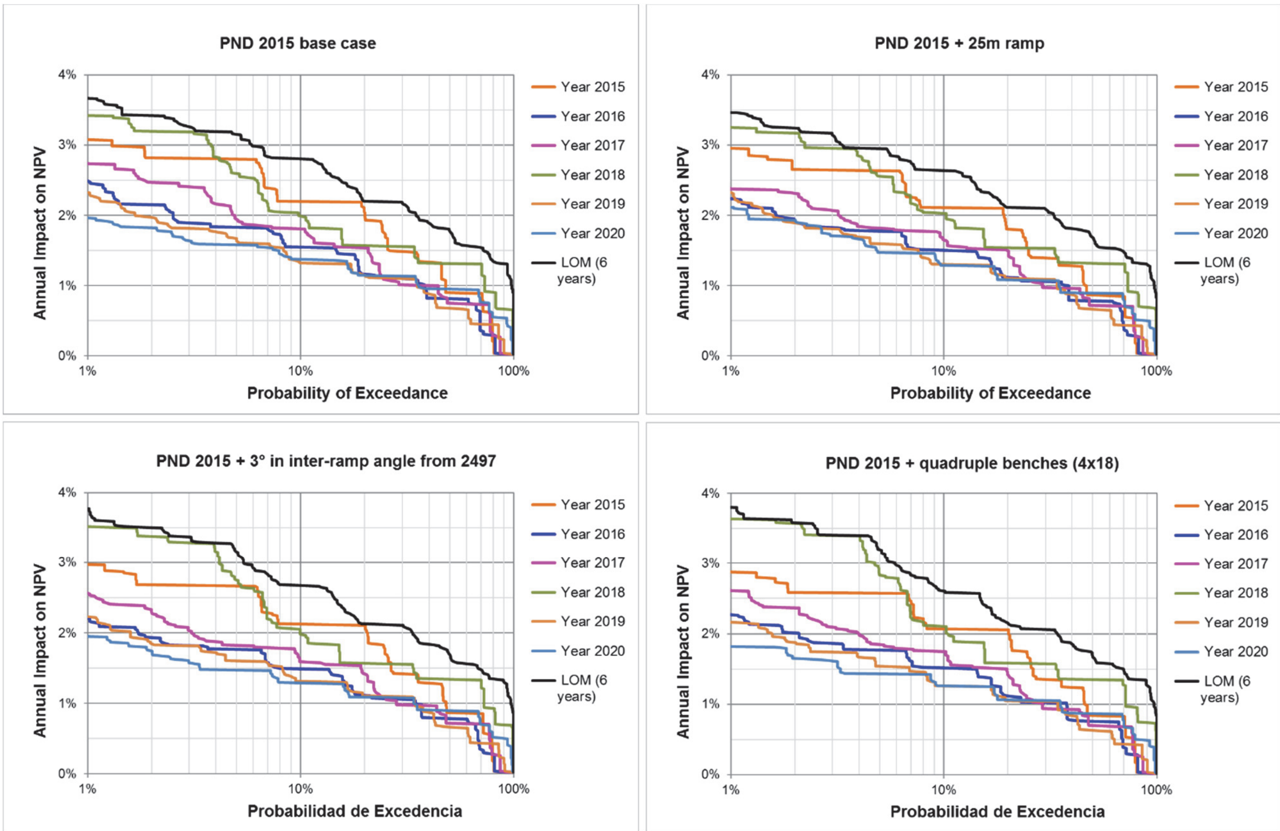


Figure 15 Economic risk maps for impacts on NPV for the four closure options of the PND 2015 mine plan

The analysis in terms of impacts on annual profits is a better way to differentiate the economic risk of the four closure alternatives. Figure 16 shows the risk maps for impact on annual profits for the four slope configurations studied. The graphs include the risk envelopes for the individual years of the mine plan and the envelope representative of the risk situation for the LOM. The graphs in Figure 16 also include risk categories of reference applicable to the six-year LOM envelopes, in the form of demarcated low (green), moderate (yellow) and high (red) risk areas.

The grayed envelopes for the individual years in the graphs of Figure 16 are included for reference, but they are not intended to be assessed with the risk category areas displayed, which are only meaningful for the LOM risk envelope. All the graphs show that there is a particular year with a notoriously high risk, which controls the LOM risk profile. The high risk envelope corresponds to year 2020, which is the final year of the mine plan when the slopes reach their final configurations for closure.

Although the risk envelopes for impact on annual profit during the LOM fall in the area of high risk for all the closure options, there are differences associated with higher levels of risk for the steeper slope configurations. The results were useful to appreciate the relative impacts when comparing the options, and to provide reference criteria to support de selection of the preferred slope configuration. The alternative selected consisted in the 3° steepening of the inter-ramp angle from bench at elevation 2,497 m, which corresponds to the design optimisation based on having steeper slopes in areas of more competent geotechnical units. The selection of the closure option also considered other operational risk aspects not included in the risk maps of Figure 16 such as those derived from the development of quadruple benches.

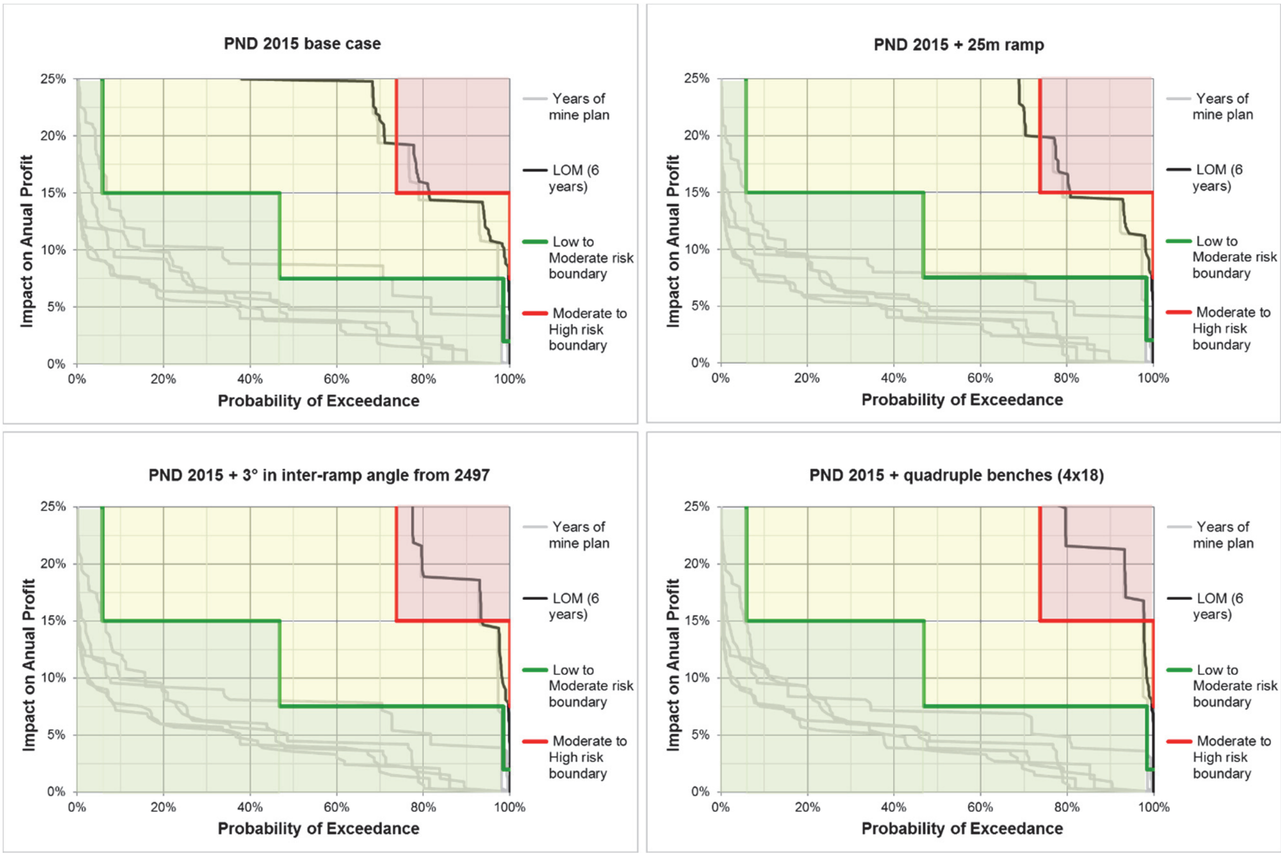


Figure 16 Reference criteria compared with the risks maps for impacts on annual profits for the LOM for the four closure options of the PND 2015 mine plan

4 Conclusion

The risk evaluation process based on the construction of risk maps for the economic impact of slope failure considers the PF of the slopes derived from geotechnical analysis, and the economic impact of those failures from cash flow analysis of the mine plan. Both type of analysis are normally based on limited data and require subjective inputs from engineering judgement and expert opinion. For this reason, it is important to carry out tuning analysis of the models used to validate their results. Tuning of the geotechnical models for the calculation of the PF of the slopes are based on observed conditions of the pit walls. The validation of the economic impacts estimated with cash flow analysis are based on historical cases of failures or detailed mining scheduling as done for real failure situations.

The risk methodology for economic impact of slope failures was used to evaluate four slope configurations for the closure of the Chuquicamata pit. The risk maps, in terms of impacts on NPV, were not sensitive enough to differentiate the risk implications of the four options evaluated. However, the risk maps in terms of the impacts on annual profits provided a reference with regard to differential risks between the options. Although the four alternatives ranked high in terms of the risk categorisation, the results indicated that the risks are driven by the expected conditions in the final year of the mine plan when the slopes reach the maximum height. The results of the risk evaluation provided reference criteria to support de selection of the preferred slope configuration consisting in the 3° steepening of the inter-ramp angle from bench at elevation 2,497 m. This alternative corresponds to the design optimisation based on having steeper slopes in areas of more competent geotechnical units. The selection of this option also considered other operational risk aspects derived from the development of quadruple benches, which are not included in the risk maps.

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