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Rock mass behaviour of deep mining slopes: a conceptual model and implications

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Abstract

The present study proposes a conceptual model to estimate the rock mass behaviour of deep mining slopes in porphyry copper deposits, which in some mines may reach more than 1 km, such as Chuquicamata (Chile) or Bingham Canyon (USA). It was proposed that deep mining slopes (more than 500 m depth), should be differentiated from shallow or less deep slopes, in the geomechanical behaviour of the rock mass. Close to surface, an elastic-perfectly plastic behaviour was generally assumed to represent the rock mass behaviour. For deep mining slopes, the behaviour of the rock mass may change to a strain-weakening or brittle response. The limit between the two geomechanical behaviours depends on the geological features of the recognised sulphide limit.

The geomechanical response of a conceptual model of a deep mining slope is analysed using two dimensional numerical models, based on a parametrisation of the wall geometry (depth and overall angle), sulphide limit depth and stress ratio (ratio between the horizontal and the vertical in situ stresses). The results of the parametric analysis were presented in terms of the factor of safety. It was found that the stress ratio does not significantly affects the factor of safety of a deep slope for the range of overall angles considered in the analysis (25–45°). From the results, a limit equilibrium relationship between the wall geometry/sulphide limit and depth was proposed.

The implications of the results of the study were related to the expected overall failure mechanism of the wall and the type of monitoring systems that should be considered.

Keywords: *deep slopes, open pit, porphyry copper deposits, sulphide limit, constitutive model, numerical modelling*

1 Introduction

Many large open pits, mostly related to metalliferous porphyry orebodies, are expected to reach depths beyond 500 m, and eventually may face a transition to underground mining, if the orebody is deep enough. Large open pits of the industry hosted by porphyry orebodies, such as Chuquicamata, Bingham Canyon or Escondida, must face long-term decisions related to the continuity of the mining activities that can take many years in advance to add maximum value to the mining business.

Current cases of deep mining slopes are limited. However, in the next decades an increase is expected based on the deepening of current open pits, and new projects, some of them with transition to underground mining. Based on the information of 14 major mining companies (Robotham 2011), it was estimated that 85% of the total cases presented a depth less than 600 m, and only 4% equal or greater than 1,000 m (Figure 1). The projection of this situation is around 17% of the cases with final depths greater than 1,000 m This trend is a major challenge for the open pit mining industry, related to the rock mass behaviour of deep slopes without a significant empirical evidence and key learnings for future geotechnical designs.

In this context, this paper attempts to study the geomechanical response of deep mining slopes through a conceptual model based on the geological feature present in porphyry copper deposits (sulphide limit). Given the cases and data supporting this study, the range of application is constrained to porphyry copper deposits only; with the potential to extend to other types of porphyry deposits.

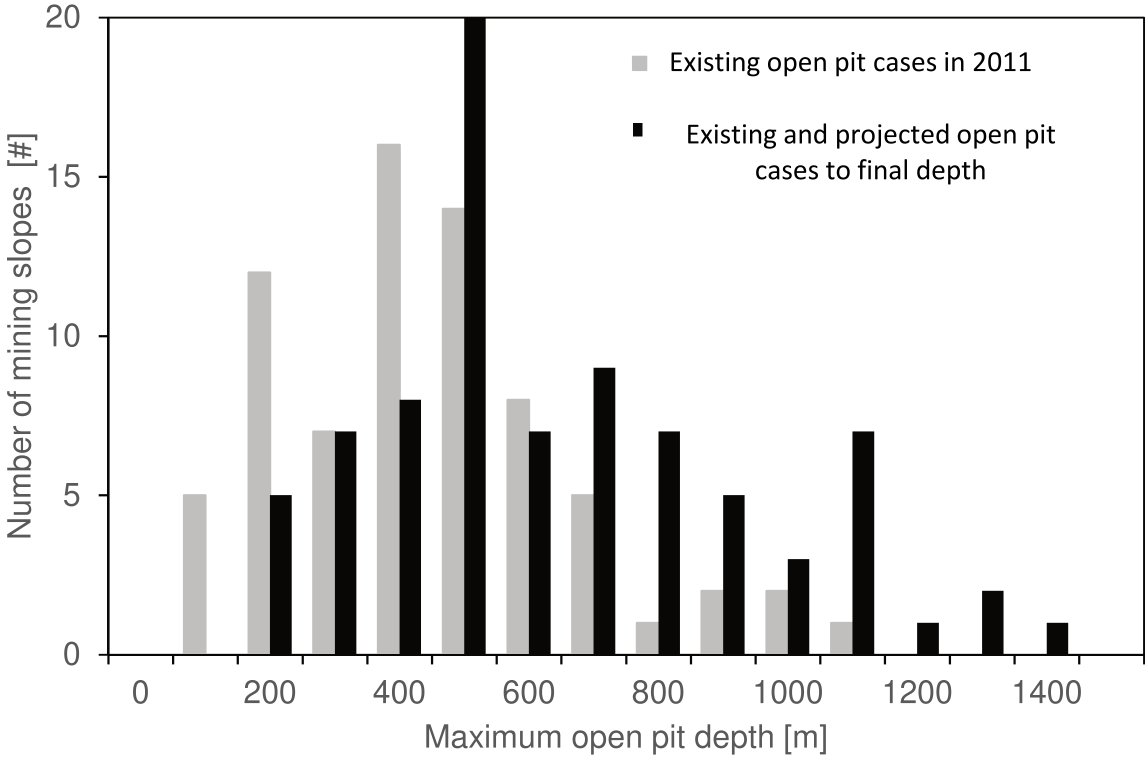

Figure 1 **Summary of maximum depths for existing and projected open pits, updated to 2011. Total of 82 cases were considered from the following companies: AGA, Anglo American, BHP, Barrick, Codelco, Collahuasi, Debswana, DeBeers, FMI, Newcrest, Newmont, Rio Tinto, Teck, Vale (Robotham 2011)**

2 Conceptual model

The development of this conceptual model is based on the understanding on the geological features of porphyry copper deposits, to address geomechanical behaviour. In this context, the identification of different geological-geotechnical domains can be modelled with constitutive models able to represent each expected behaviour. The result of this exercise provides the opportunity to differentiate shallow/less deep slopes and very depth slopes.

2.1 Sulphide limit and rock mass behaviour

Large open pit mining operations are hosted in porphyry copper deposits, which are defined in geological terms as big volumes (10–100 km^3) of hydrothermally altered rock masses (Sillitoe 2010). These deposits are characterised by a sequence of geological alterations, generally, according to an evident vertical pattern, as a result of repetitive geological processes. These processes address the features and characteristics of the rock masses during mineralisation, and the following hydrothermal processes, and the generation of secondary concentration (enrichment) by the action of surficial fluids (Sillitoe 2010). These geological processes generate the relevant transformations of the rock masses and its mechanical characteristics, either the macroscopic fabric (structural systems, filling) and microscopic characteristics (strength). The mineralisation process in such rock masses, generates varying zones (lateral and vertically) related to the proximity with: i) thermal source (depth); ii) penetration limit of the meteoric fluids (surface); iii) deformation processes triggered after genesis of the deposit. Thermal source corresponds to magma that is projected from deeper zones to surface onwards. Meteoric fluids correspond typically to rainfalls and/or surficial water flows. Finally, deformation processes are associated to changes in the regional stress field that affects the deposit locally.

Figure 2 shows a scheme of vertical and lateral distribution of the sequence of alterations described, commonly found in porphyry copper deposits (Sillitoe 2010; Sillitoe & Perelló 2005; Weis et al 2018). The distribution of alteration zones is the result of a process developed over the brittle ductile transition zones associated to the thermal effect of intrusion of the porphyry, between 1.5 km and 3 km depth (Sillitoe 2010). Argillic alteration is concentrated greatly in the upper part of the deposit, associated to major interaction with meteoric fluids (see Figure 2). This alteration has associations of clay, generating rocks with a lowered strength.

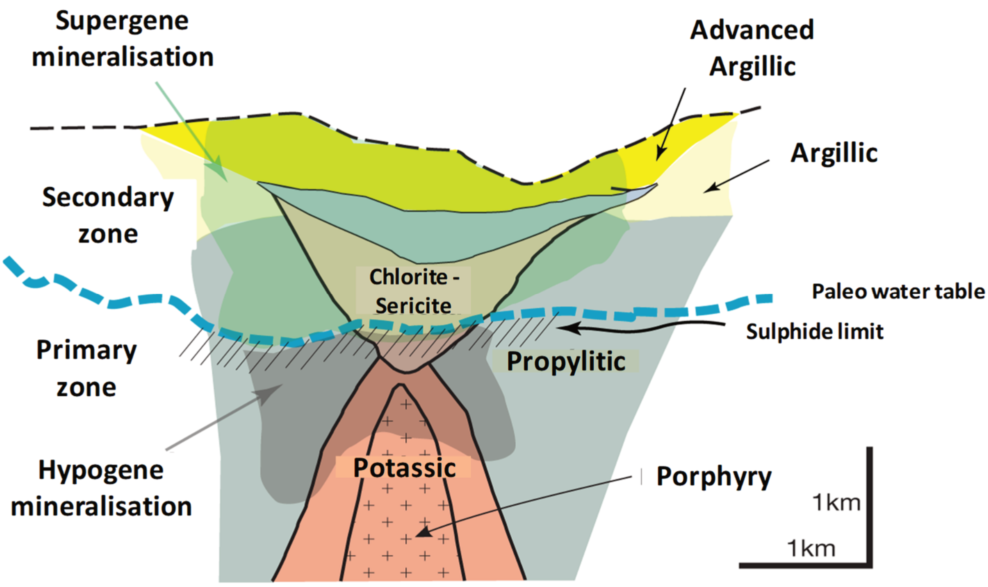

Figure 2 Generalised scheme of sequence of alteration-mineralisation of porphyry copper systems, indicating the secondary-primary limit, usually associated to the limit of sulphide presence (modified from Sillitoe 2010)

In general terms, the alteration zone is usually sequenced according to depth: i) potassic alteration (deeper); ii) propylitic alteration; iii) Chlorite-sericite alteration (phyllic); iv) Sericite alteration, and v) Argillic alteration in the surficial zones.

All of this addresses two clear zones in porphyry copper deposits: i) primary hypogene zone (deeper and more competent); ii) secondary supergene zone (surficial and less competent). In this context, percolation limit of surficial water is responsible for generating such zones, geologically identified by the presence of sulphides that fill the zones of the rock mass that are more permeable associated to the deeper zone, and not observed in the surficial secondary zone. For this reason, under the geological characterisation of deposits, it is established the sulphide limit, or sulphide boundary, as a relevant boundary for both supergene and hypogene domains. Figure 2 shows the sulphide limit near the maximum phreatic level generated by the percolation of surficial fluids (palaeo watertable), and can be located to 1 km of depth.

The conceptualisation of the sulphide limit has an impact on the geotechnical rock mass parameters measured at depth. Figure 3 shows an exercise of the distribution of the Geological Strength Index (GSI) for Escondida open pit. This case shows a clear change of the GSI values between 625 and 650 m below the surface, providing an estimation of the sulphide limit location. Deeper volumes are likely to exhibit higher GSI values and then a higher rock mass strength. Figure 4 shows a trend from higher values in the potassic alteration to lower values in the argillic alteration, even for different lithologies.

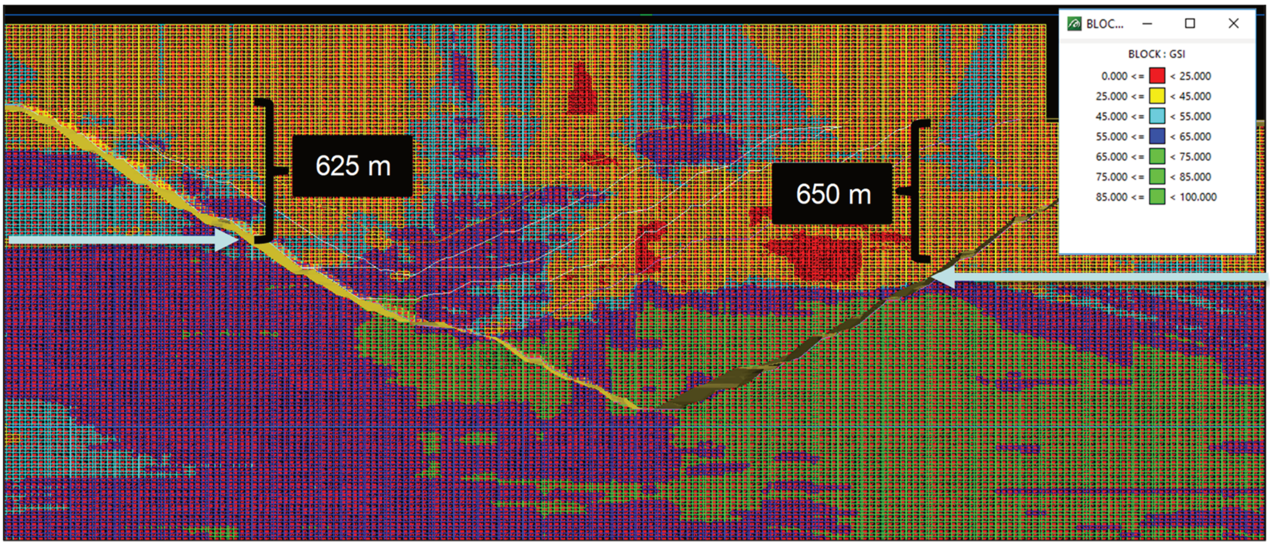

Figure 3 Geological Strength Index (GSI) distribution of a representative section of Escondida open pit mine. The block model shows a GSI consistently greater than 55 for depths between 625 and 650 m below surface. This depth is presumable related to the location of the sulphide limit

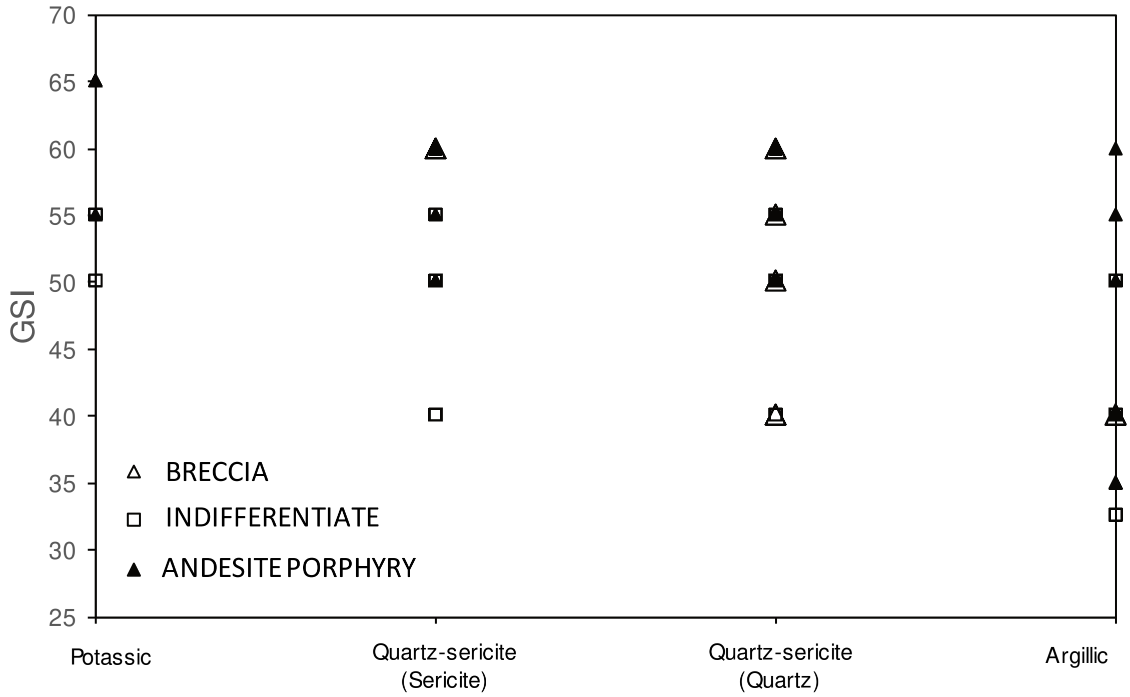

Figure 4 Relationship between Geological Strength Index (GSI) and grades of alteration based on 1,775 mapped samples from BHP sites in Chile. A decreasing trend of GSI values is observed from potassic to argillic alteration

Intact rock strength is an additional indicator that can be used to show a clear trend from potassic to argillic alteration, in order to confirm the lower strength at shallower depth, and higher strength for deeper zones of the deposit. Figures 5 and 6 show evidence from Chuquicamata and BHP sites (Cerro Colorado and Spence) respectively, where the uniaxial compressive strength (UCS) has a direct relation with the level of alteration, for different rock types.

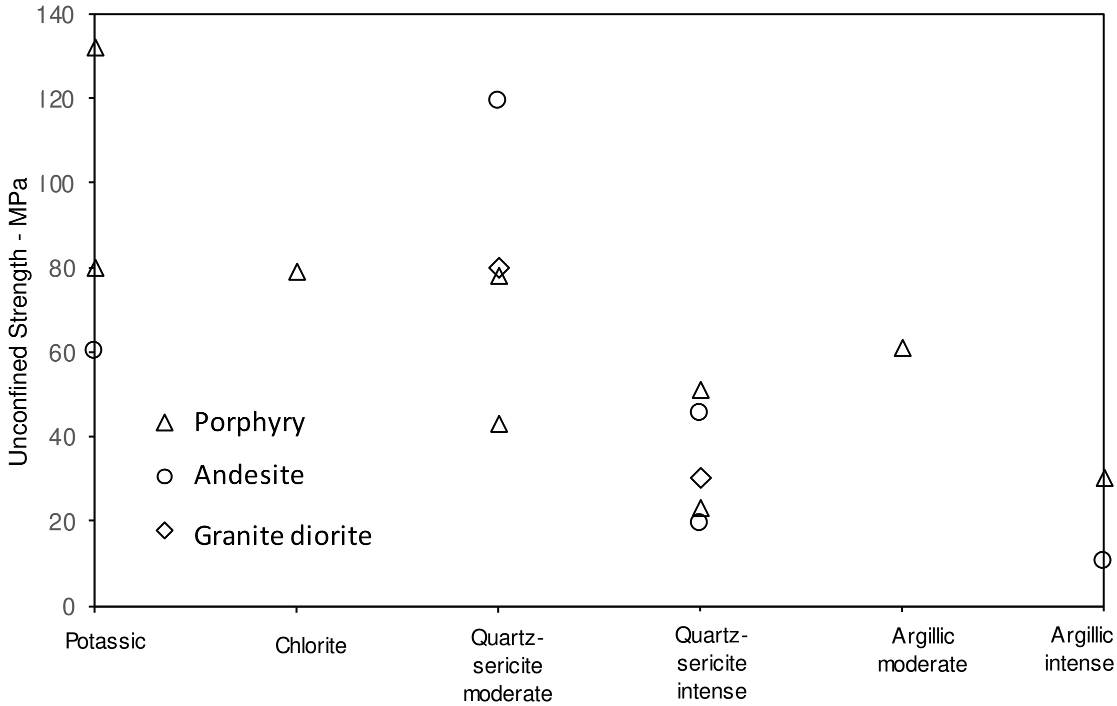

Figure 5 **Relationship between the uniaxial compressive strength of intact rock and the type of alteration, based on Chuquicamata samples (Hoek et al. 2000)**

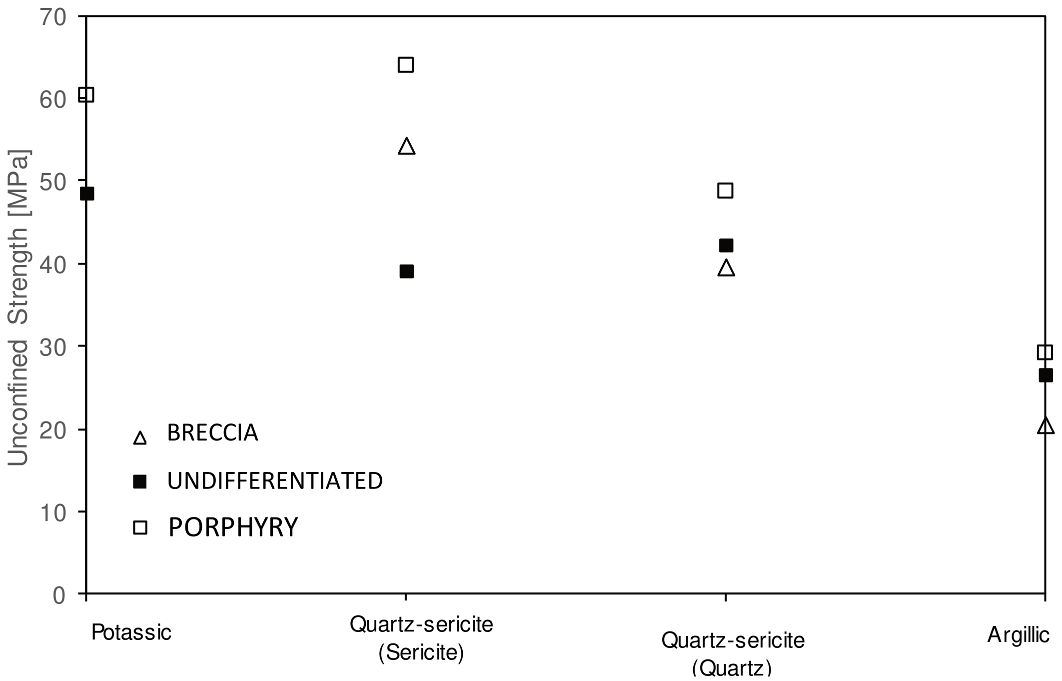

Figure 6 **Relationship between the uniaxial compressive strength of intact rock and the type of alteration for different types of rock. Average values based on 1,775 samples from BHP sites in Chile**

Considering the trend of the GSI and UCS parameters in conjunction with the geology understanding a change in the geotechnical rock mass quality can be validated at depth. In addition, strength seems to be higher at depth but UCS represent a peak value not the complete expected behaviour. In this regard, Figures 7 and 8 show the results of laboratory tests for samples from a BHP copper mine (Spence site), performed with controlled deformation to get the post-peak behaviour. These tests correspond to hypogene rock types associated to deeper areas of the deposit. With the purpose to account intact rock results, it was considered only matrix failure tests, and consistency between different levels of confinement.

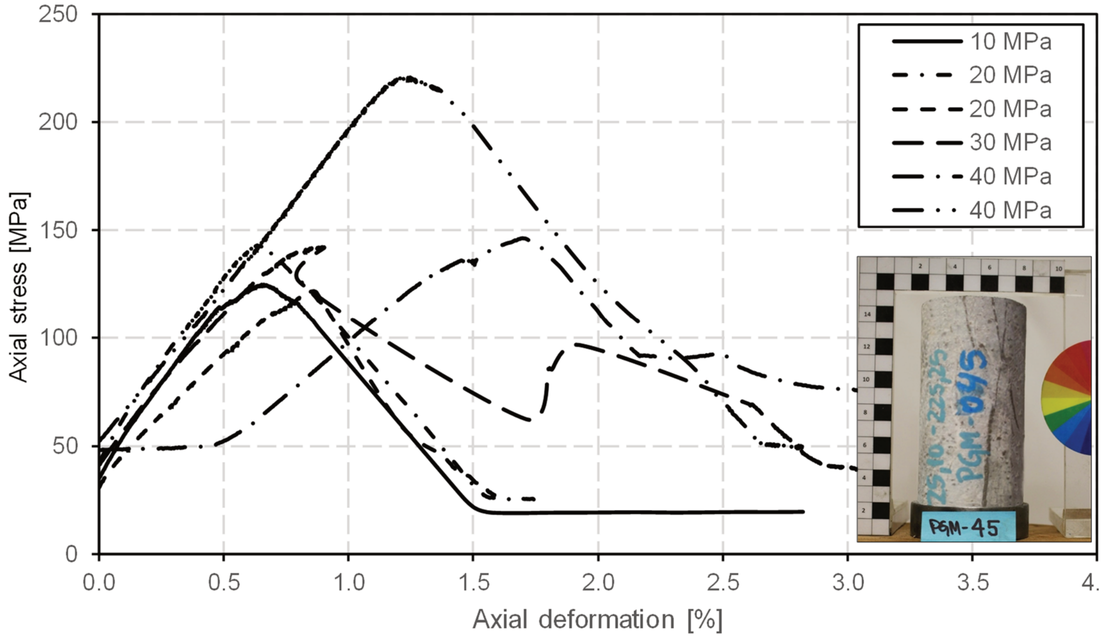

Figure 7 Post-peak laboratory tests (controlled deformation) at different levels of confinement of 10, 20, 30 and 40 MPa. Porphyry 1 – Hypogene unit

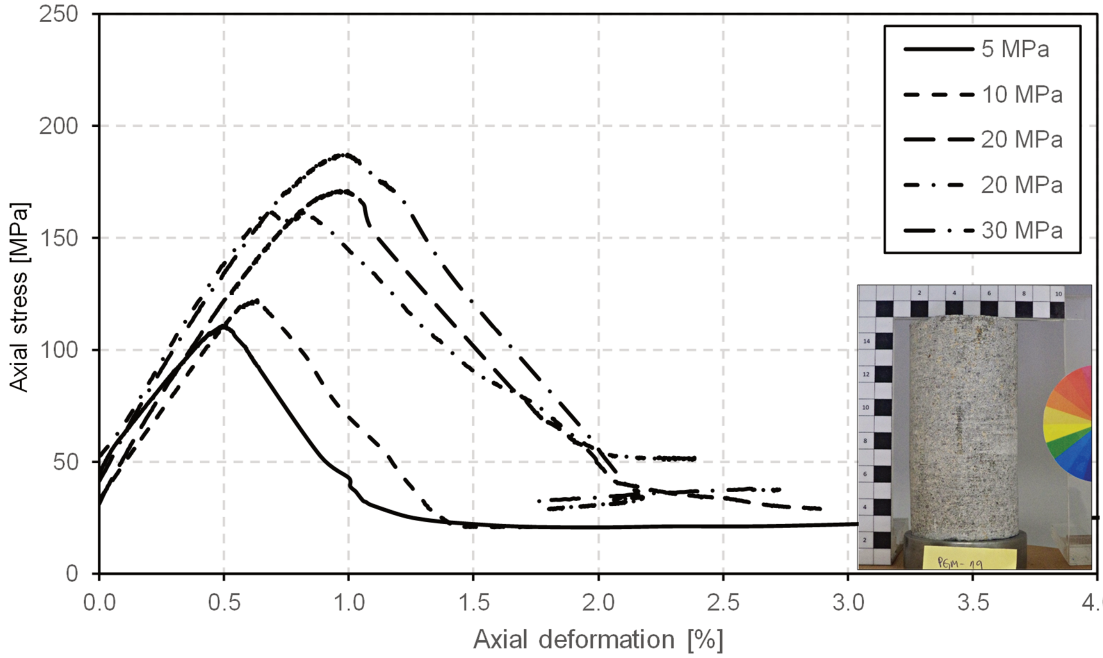

Figure 8 Post-peak laboratory testis (controlled deformation) at different levels of confinement of 10, 20, 30 and 40 MPa. Porphyry 2 – Hypogene unit

All of these backgrounds and evidence can be organised into one conceptual model to explain differences between shallower and deeper open pit mines. Figure 9 show a scheme with the expected behaviour going deeper supported by the geology models developed for porphyry copper deposits, and geotechnical parameters with the alteration sequence. This conceptual model allocates a (sulphide) limit as a boundary to divide the rock mass into different geomechanical behaviours.

It worth noting that this conceptual model refers to the sulphide limit, to be closer to the upper limit of application for the GSI (Marinos et al. 2005).

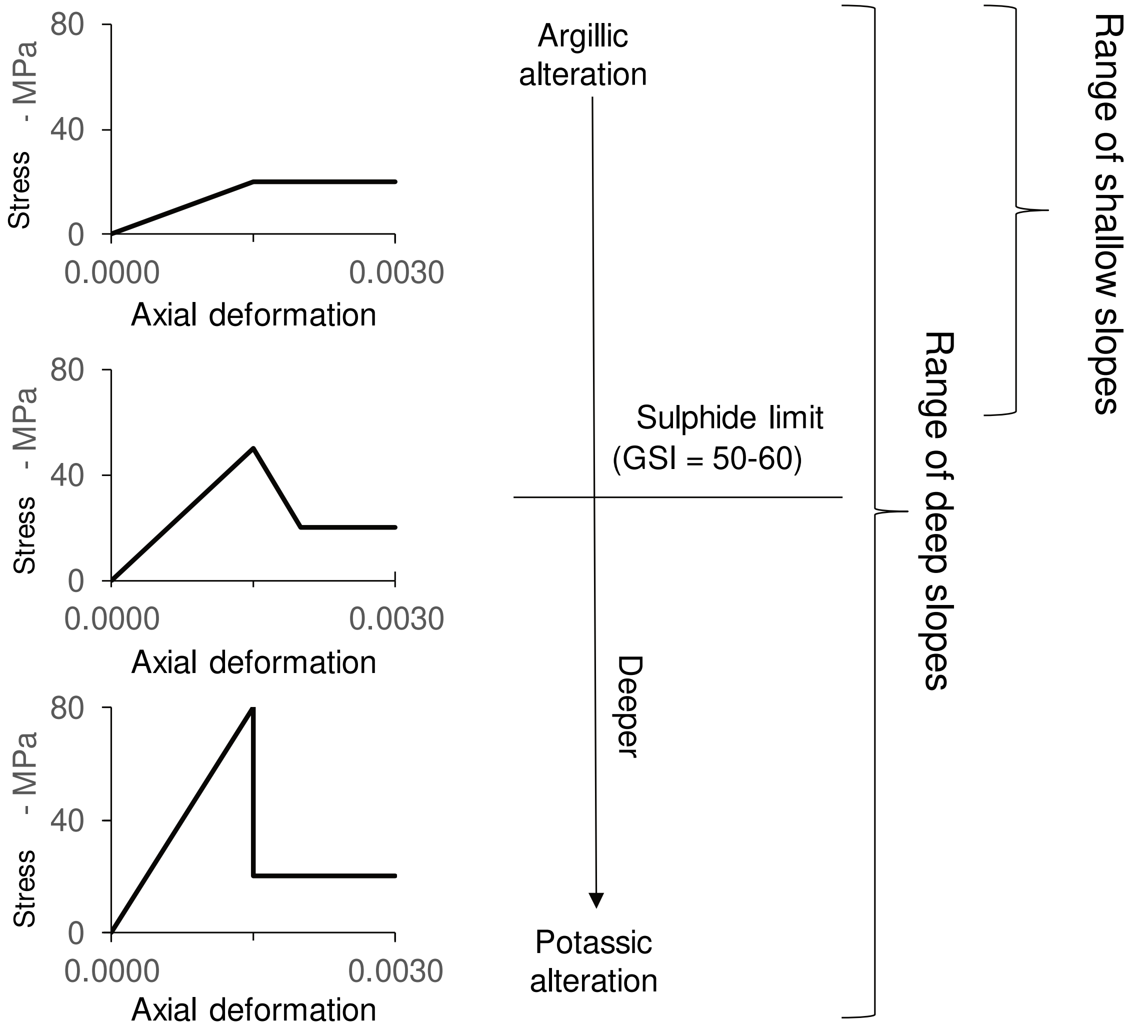

Figure 9 **Proposal of the conceptual model considering post-peak rock response for different depths for porphyry copper deposits**

2.2 Constitutive models and numerical modelling

The conceptual model showed in the previous section can be implemented into a numerical model in order to obtain results and understand the implications for mine design. The model considers two types of rock masses separated by the sulphide limit (Figure 10). The upper rock mass can be modelled by an elastic-perfectly plastic, and the lower rock mass as a strain-weakening to take into account the behaviour shown in Figures 8 and 9.

The peak strength can be estimated with conventional scale relationships from intact rock scale to rock mass scale. Post-peak strength has to be included into the numerical model using an approach suitable with the capabilities of the software RS2 (used in this work) and able to reflect the stress-strain behaviour in a proper manner. For this reason, elastic-brittle plastic response is included using the approach developed by Diederichs (2003) based on the damage zones measured in the experimental tunnel in Lac du Bonnet granite. The use of a residual envelope beyond the damage initiation, after cohesion weakening and friction strengthening, is reflected in a steeper curve that cross the peak strength envelope at a certain level of confinement (Figure 11). This model is referred to as the DISL (Damage Initiation Spalling Limit), and reflects the brittle response in a simple way and easy to be included in conventional numerical model using only two strength envelopes.

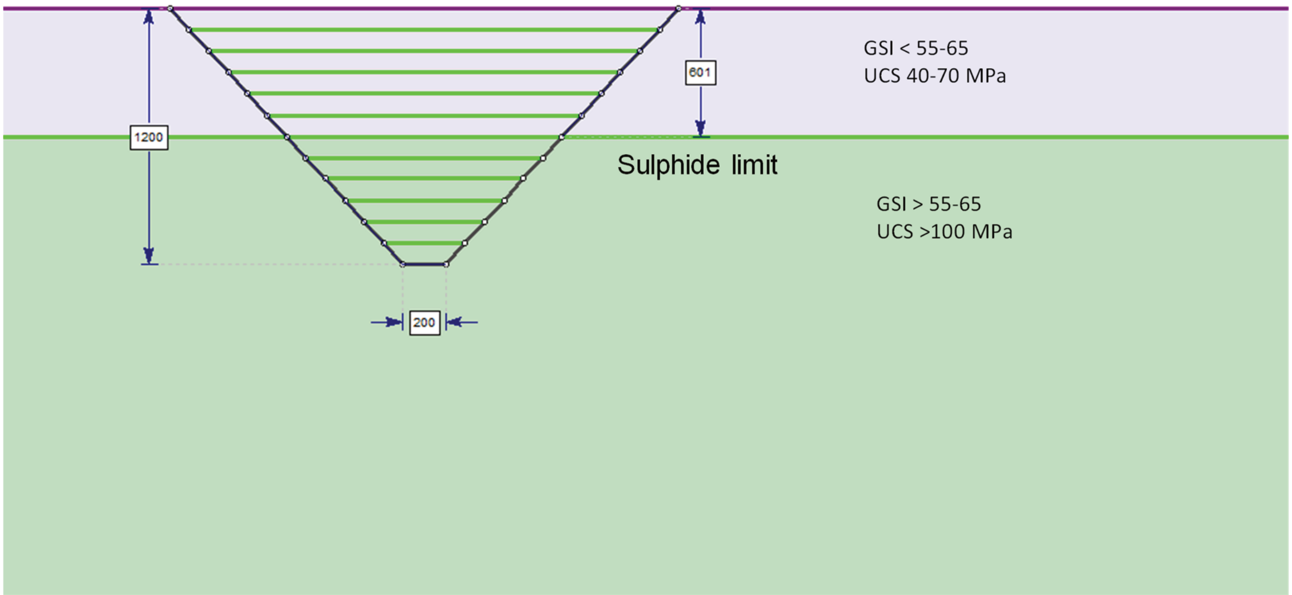

Figure 10 Conceptual model and geomechanical rock mass response with depth

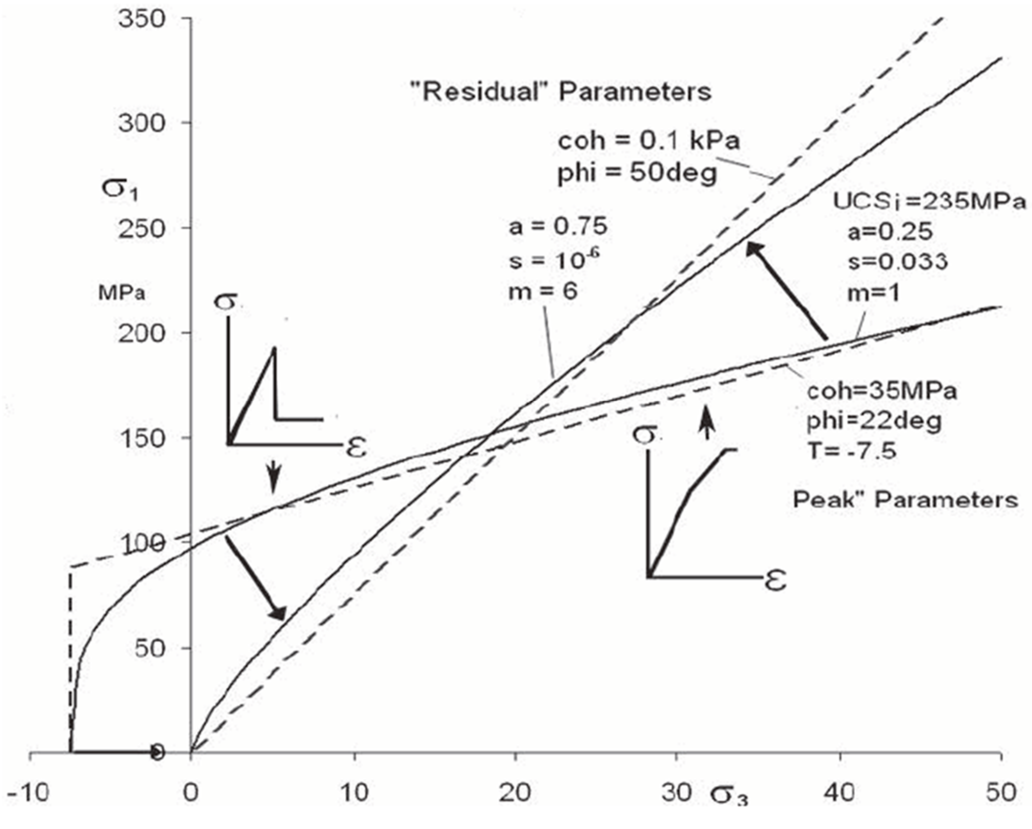

Figure 11 Peak and post-peak parameters used for a finite elements analysis (Phase2) of the experimental tunnel Lac du Bonnet granite. Arrows show 'strain-weakening' and 'strain-strengthening' behaviour beyond peak envelope (damage initiation threshold), for DISL (Damage Initiation Spalling Limit), model (Diederichs 2003; Carter & Diederichs 2008)

Following the identification of the constitutive models, geotechnical parameters must be estimated to reflect both above and below sulphide limit type of rock masses. Hoek & Karzulovic (2000) proposes a set of parameters to be used as a reference for different type of rock masses from poorer to more competent cases, in terms of peak strength. This reference was reviewed, and the parameters estimated for some of the units present in Escondida mine, with the final results shown in Table 1. Using the recommendations of Diederichs (2003) and Carter & Diederichs (2008), the residual (post-peak) strength parameters were estimated. The final curves obtained for both rock masses are graphically shown in Figure 12. In this figure, it can be observed a lower strength assigned to the rock mass above the sulphide limit. The rock mass below the sulphide limit shows a higher strength modelled with two strength curves peak and post-peak, showing with an arrow the direction from elastic to plastic state.

Table 1 Parameters used for the finite element model, based on referential Escondida pit units and literature reference (Hoek & Karzulovic 2000; Hoek et al. 2002)

State of failure	Geotechnical parameters	Secondary rock mass above sulphide limit	Primary rock mass below sulphide limit
Peak strength envelope	σ_{ci} (MPa)	42.7	110.0
	m_i	10	28
	GSI	45	75
	E_i (MPa)	34,600	73,000
	m_b	1.44	11.47
	S	0.0022	0.0622
	A	0.508	0.501
	E_m (MPa)	7,738	59,594
Post-peak strength envelope	m_b	1.44	7.00
	s	0.0022	0.0001
	a	0.508	0.750
	Poisson's ratio	0.34	0.22

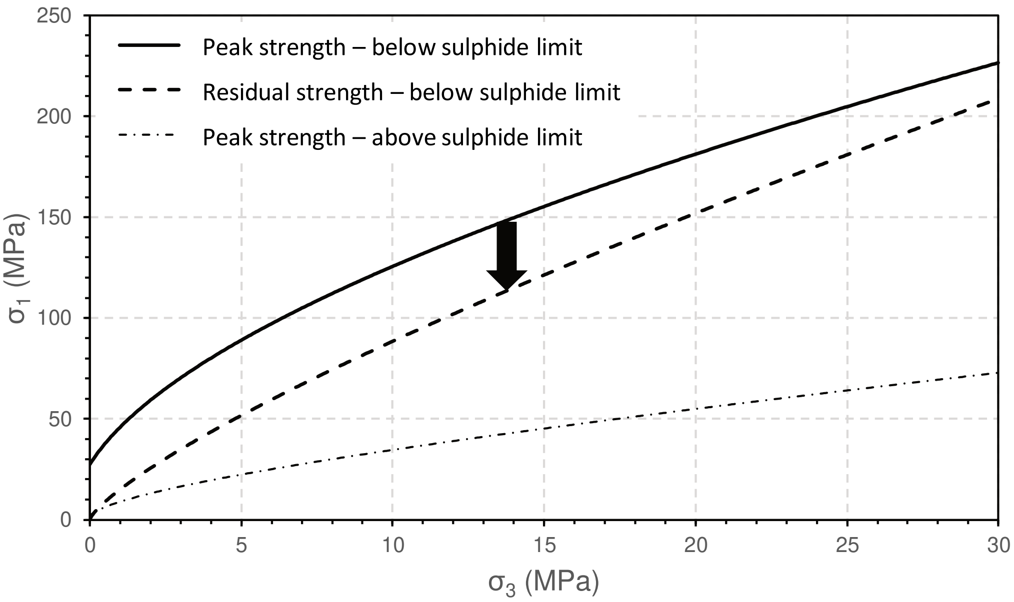

Figure 12 Peak and post-peak strength envelopes for rock masses above and below sulphide limit, based on the parameters of Table 1

The numerical model considers 6-node triangles of 15 m size close to the walls, to be representative of one single bench. The size of the finite elements increases away the face walls and approaching to the boundaries of the model box (Figure 13). Based on suitable modelling recommendations (Wyllie & Mah 2004), it was included fixed nodes at the corners of the box, vertical rollers on the sides (no horizontal displacements) and horizontal rollers at the bottom (no vertical displacements). The size of the model box was estimated using the following rule to avoid numerical artefacts in the results:

$$B1 > \frac{h}{\tan(\alpha)} \tag{1}$$

$$B2 > \frac{h}{2} \tag{2}$$

where:

B1 = horizontal lateral extension of the box model, measured from the pit border.

B2 = vertical extension of the box model, measured from bottom of the pit.

h = open pit depth.

α = overall slope angle.

B1 and B2 were estimated taking the most critical case corresponding to an open pit of 2,000 m depth and 25° overall angle. As a result, the model box has a size of 18,200 m width and 5,000 m height (Figure 13). The width at the bottom of the pit was fixed in 200 m for all cases, based on operational rules justified in providing enough space for one shovel and two trucks to work.

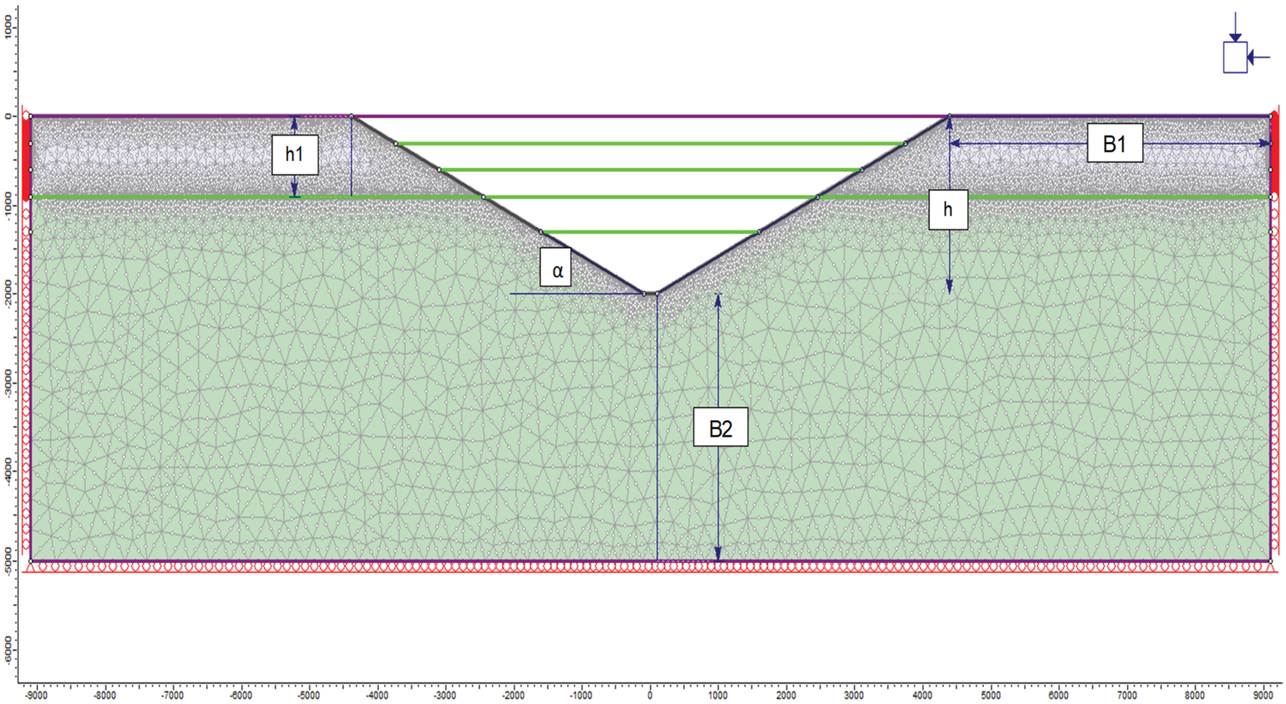

Figure 13 Geometry parameters and boundary conditions of the model (based on Willie & Mah 2004)

Once boundary conditions are defined, it is necessary to identify the parameters and ranges to generate all the cases to be simulated. The parameters considered for the analysis are sulphide limit (h1), open pit depth (h), overall pit angle (α) and stress ratio (k).

Based on Sillitoe (2010), sulphide limit can be either very surficial because of the erosion of the upper cap or very deep as much as 1 km. Based on deeper shallower open pits cases (Chuquicamata and Spence), the maximum and minimum value for h1 will be 900 m and 300 m, respectively. An intermediate case of h1 = 600 m is considered, based on the case of Escondida (Figure 3).

Parameter for the open pit depth (h) were considered with values of 500 m, 800 m and 1,000 m. In an exploratory way, it was also considered two additional hypothetic cases of 1,500 m and 2,000 m open pit depth. Overall pit angle was considered with values of 25°, 35° and 45° to cover a reasonable range of cases. Finally, stress ratio was considered with values of 1.0, 1.5 and 2.0 to cover several potential cases independently of depth.

Considering all combinations of the parameters, and excluding redundant cases, a total of 171 cases to simulate are obtained and implemented in the numerical model (Table 2).

Table 2 Parameters used to generate all the combinations considered in the numerical analysis

Sulphide limit depth (m)	Pit depth (m)	Overall pit angle	Stress ratio
H1	**h**	**α**	**K**
0	500	45	1.0
300	800	35	1.5
600	1,000	25	2.0
900	1,500	–	–
–	2,000	–	–

3 Rock mass response at great depth

The 171 simulations were run on the numerical model to obtain results and identify the impact of the parameters on the slope stability conditions.

3.1 Implications on the effect of the stress ratio

In situ stress conditions is one the less studied parameters in terms of the impact on large open pit stability. To contribute to clarify this point, it was checked how the stress ratio affects the safety factor for different open pit geometries. Figure 14 shows the results in terms of a graph of the safety factor as a function of the overall angle, for different pit depths, considering all cases in which the safety is equal or greater than 1, and stress ratios varying between 1.0 and 2.0. It is observed a strong relation between safety factor and overall angle for each case, but it is not possible to identify a clear trend for the different stress ratios.

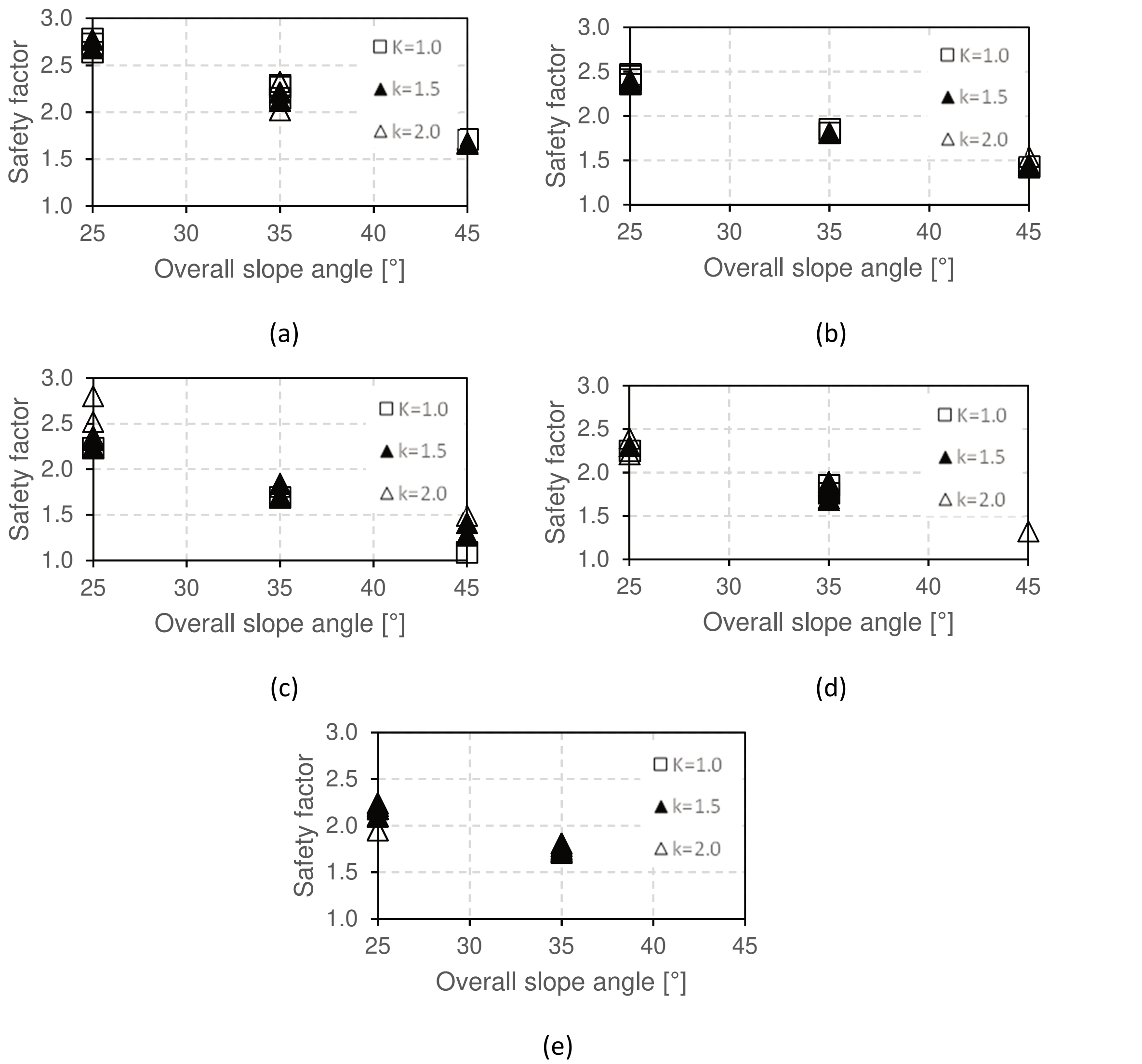

Figure 14 Factor of safety as a function of overall angle for different stress ratio and different pit depths: (a) 500 m; (b) 800 m; (c) 1,000 m; (d) 1,500 m; and (e) 2,000 m

3.2 Implications on the global failure mechanisms

To evaluate the global failure mechanism as a function of depth a case with a sulphide limit located 600 m below the surface and overall pit angle of 35° is considered. Figures 15 and 16 present the results in terms of the yield elements by shear and tension, respectively. For depths lower than 1,000 m it is observed that shearing dominates as a failure mechanism, concentrated in the upper part of the slope until the sulphide limit. As depth is increased, shearing still show some preference concentration close to the upper part of the sulphide limit, but more equally distributed along the slope (Figure 15). It is interesting to see how the failure is formed and the propagation is constrained by the sulphide limit, which is clearly shown in Figures 15(a) and 15(b). In this regard, shallower slopes tend to show failure by shear, and constrained by sulphide limit. The response of the model is consistent with the expected behaviour. The implication is that the selected sets of parameters are consistent.

On the other hand, deeper slopes show more failure by tension in the lower part of the walls (Figure 16). The change in the failure mechanism with depth, indicates that the traditional types of monitoring and instrumentation (inclinometer, time-domain reflectometer, radar etc.) should be complemented with other types of instrumentation, such as microseismic systems, in order to detect in a more integrated manner this types of potential instabilities.

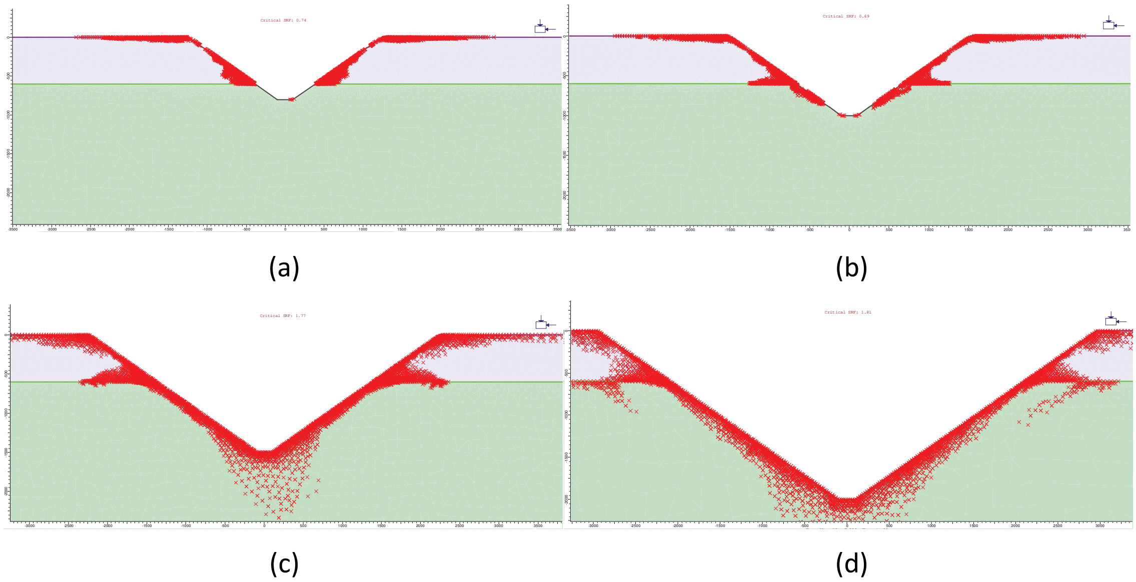

Figure 15 Shear yield elements for a sulphide limit fixed at 600 m below the surface, overall slope angle of 35° and different pit depths: (a) 800 m; (b) 1,000 m; (c) 1,500 m; and (d) 2,000 m

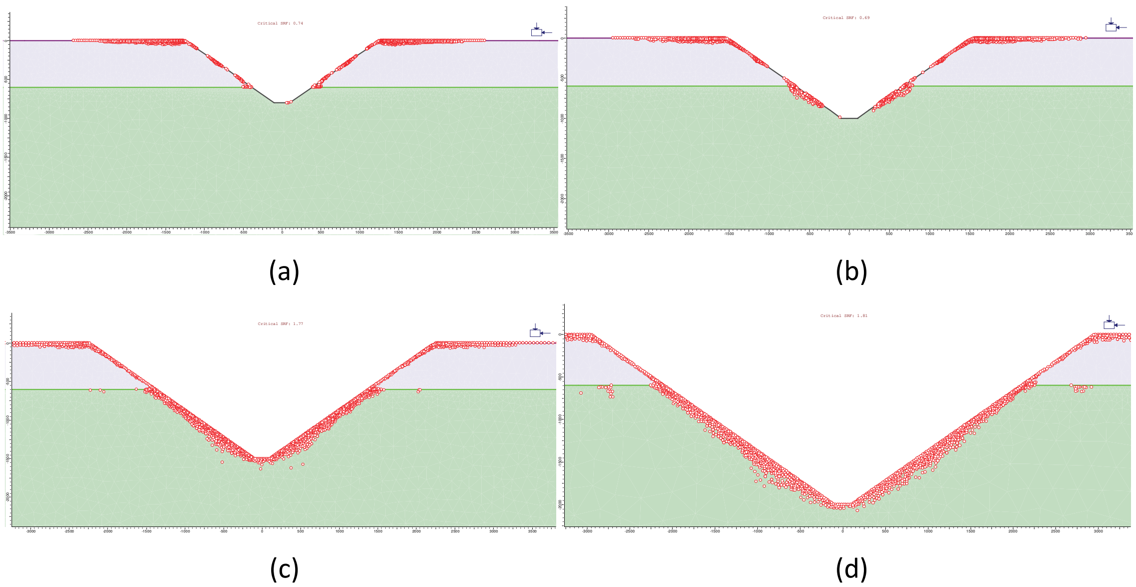

Figure 16 Traction yield elements for a sulphide limit fixed at 600 m below the surface, overall slope angle of 35° and different pit depths: (a) 800 m; (b) 1,000 m; (c) 1,500 m; and (d) 2,000 m

3.3 Proposal of stability chart

Read & Stacey (2009) showed different examples of chart to approach slope stability conditions, based on empirical methods for slope design. In this regard, there are charts that relates slope height/depth versus overall angle, and geometry indicators (h/tan(α)) that relates to rock mass quality (RMR), useful to have an idea in early stages. Going forward with a chart of this kind, it was introduced sulphide limit in the equation, and a new ratio (h1/(h/tan(α))) was developed to relate with the safety factor. Figures 17(a)–17(d) show this ratio versus safety factor, with a clear relation between them for each case of pit depth, as validation of the proposed chart to inform a certain stability condition.

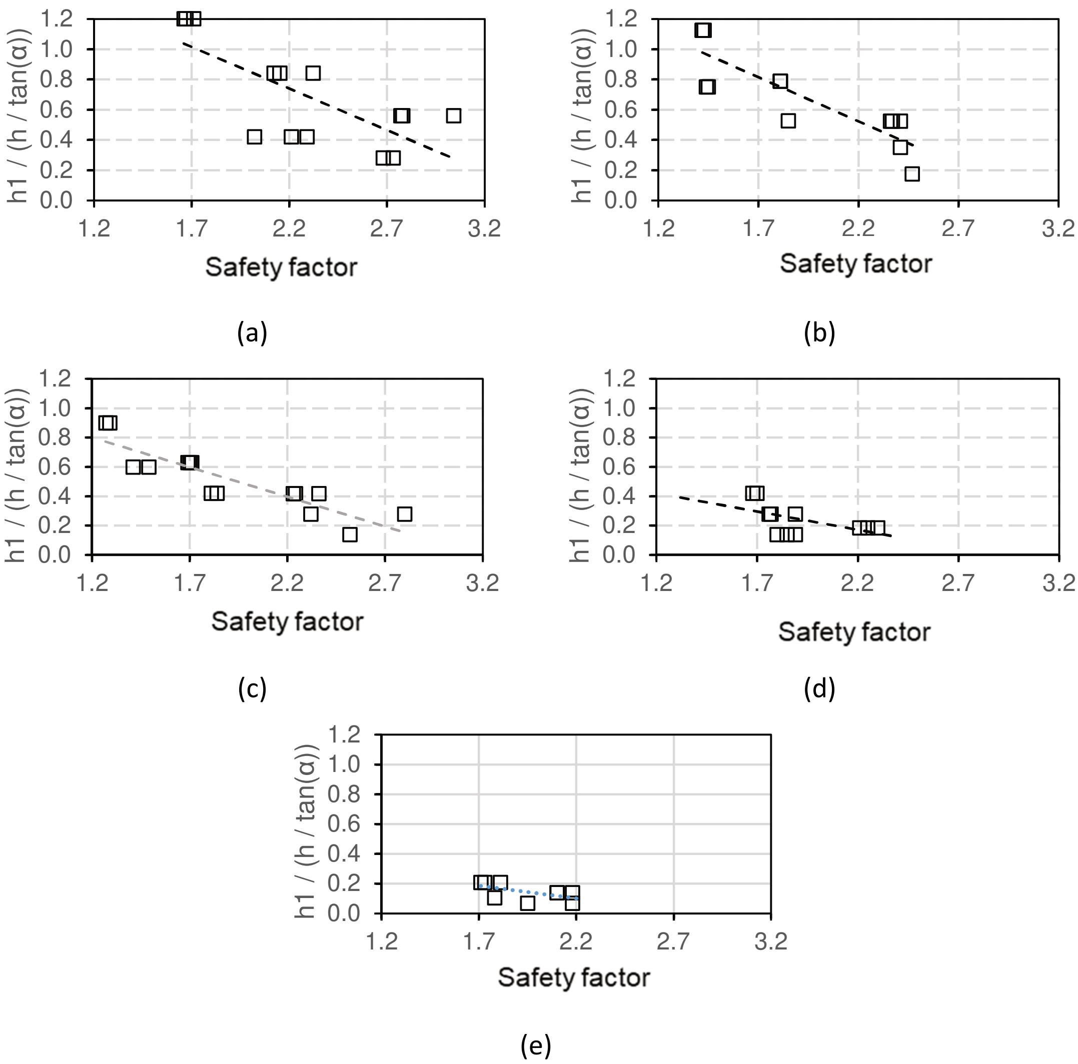

Figure 17 Sulphide limit/slope geometry ratio versus safety factor at different depths of: (a) 500 m; (b) 800 m; (c) 1,000 m; (d) 1,500 m; and (e) 2,000 m

Based on this result, it was taken all the points with the minimum safety factor but still greater than 1. These points were plotted in a graph but taking the depth in x-axis, and the moving the safety factor to the ratio, to obtain a boundary to separate stable and instable deep slopes (Figure 18).

Figure 18 shows the new ratio (h1/tan(α)/FS) versus depth (h) for all minimum safety factors that are greater than 1, to trace a boundary for stable and instable zones. Based on public information present in various papers (Tooker 1990; Ward 2015; Septian 2016; Ossandón et al. 2001) and BHP information, references points were plotted for Escondida, Chuquicamata and Bingham Canyon, as validation of this approach.

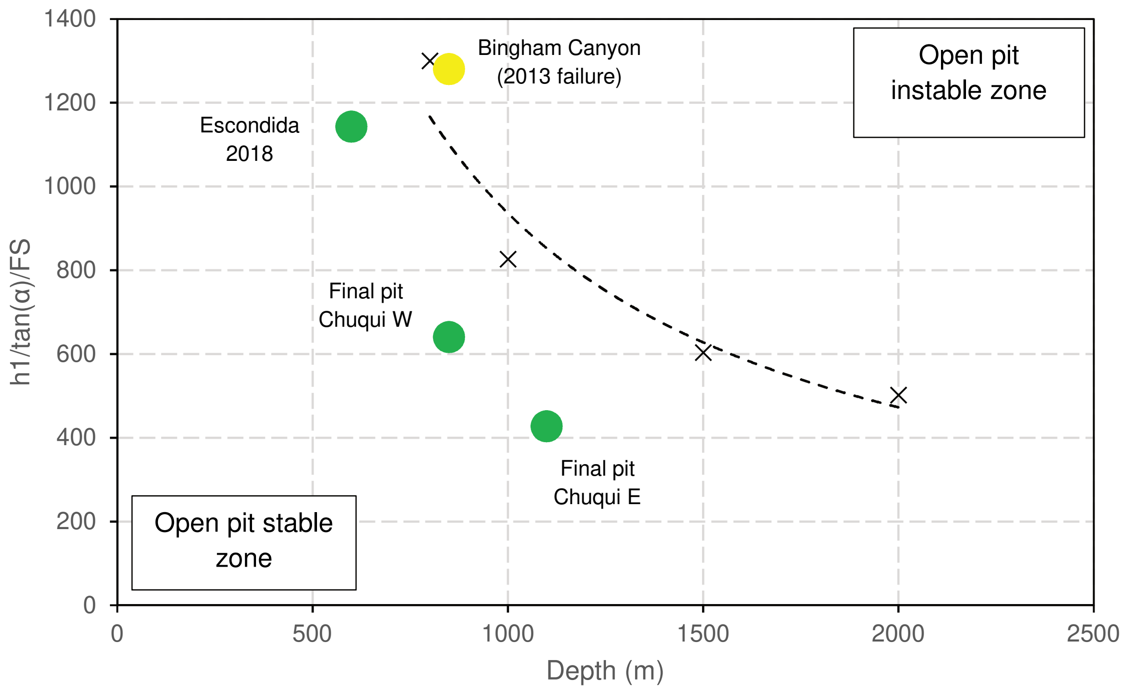

Figure 18 **Stability chart proposed for conceptual analysis of very deep open pits based on public parameters of several authors (Tooker 1990; Ward 2015; Septian 2016; Ossandón et al. 2001)**

3.4 Considerations for slope stability analysis

Based on the conceptualisation and results presented in this work, considerations for assessment of deeper rock slopes in open pits are proposed as follows:

1. Estimate the depth of sulphide limit, based on geotechnical parameters such as GSI and UCS.
2. Identify the geotechnical domains above and below the sulphide limit, to address the laboratory testing campaign using controlled loading and controlled deformation tests, to obtain insight into the geotechnical behaviour of the constitutive models.
3. Estimate geomechanical properties of peak strength for units above the sulphide limit, using triaxials performed by controlled loading. Estimate failure envelopes for confinement levels in relation with the location of sulphide limit.
4. Estimate geomechanical properties of peak/post-peak strength for units below the sulphide limit, using triaxials performed by controlled deformation. Estimate failure envelopes for confinement levels related to the zone between the sulphide limit and maximum depth of the open pit.
5. Identify preliminary stable geometry configurations using the stability chart developed in this work, for conceptual design of the deep open pit.
6. Implement the geometry of the deep open pit, and assign failure envelopes according to the following criteria:
   a. Units above sulphide limit: elastic-perfectly plastic behaviour based on peak failure envelopes, using an accepted criterion for rock mass such as Hoek–Brown or Mohr–Coulomb.
   b. Units below sulphide limit: assume strain-weakening, and assign both a peak failure envelope and residual (post-peak) failure envelope, using an accepted criterion for rock such as Hoek–Brown or Mohr–Coulomb.

4 Conclusion

The rock mass of porphyry copper deposits has been conceptualised based on geological and geotechnical backgrounds known in the industry (literature) and BHP sites. This conceptualisation was implemented in a numerical model to analyse very deep mining slopes, to obtain the following conclusions:

1. Based on literature references and BHP geotechnical databases of copper sites, it was accounted for the existence of a vertical variation of geotechnical parameters, such as unconfined intact rock strength and GSI, identifying shallower and deeper geological environments in porphyry copper deposits.
2. The existence of this geological vertical variation in porphyry copper deposits exposes at least two domains or geotechnical environments, both associated to the sulphide limit, whose geomechanical behaviours are different and, as such, needed to be properly considered in the analysis of very deep slopes.
3. Parameters of slope geometry, sulphide limit and in situ stress conditions were varied in a range representing large open pits expected conditions, and implemented in a numerical model to run 171 simulations. Based on it, a sensitivity analysis showed relevant findings for expected stability conditions, in which some parameters showed more impact (slope geometry and sulphide limit) rather than other with no clear impact on changes in stability conditions (in situ stress).
4. In situ stress ratio, in a range of 1.0–2.0, does not affect the safety factor of deeper slopes.
5. For all stable cases (safety factor equal or greater than 1), slope geometry and sulphide limit relates to slope depth. This can be expressed in terms of a stability ratio measured as h1/tan(α)/FS, which relates to slope depth (h), with the potential to highlight a technical boundary for stable and unstable pits. This is a useful result for an order of magnitude study phase, to project geotechnical feasible configurations of mining slopes, considering geotechnical aspects in expected future transitions to underground mining.
6. Failure mechanisms are of different kind above and below the sulphide limit. In this regard, it is expected to have a concentration of the slope failure above the sulphide limit. Nevertheless, the failure can affect the overall wall beyond certain depth estimated in 400 m below the sulphide limit. This impacts the design, in terms of the volume involved in the failure mechanism, which depends on this geological feature, and increasing with depth.
7. Some considerations were proposed for slope stability assessment in cases of deeper large open pits, which includes a geology feature (sulphide limit), not considered before in traditional geotechnical analysis.

Acknowledgement

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