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Geotechnical design considerations for 'nose' geometries in pit design

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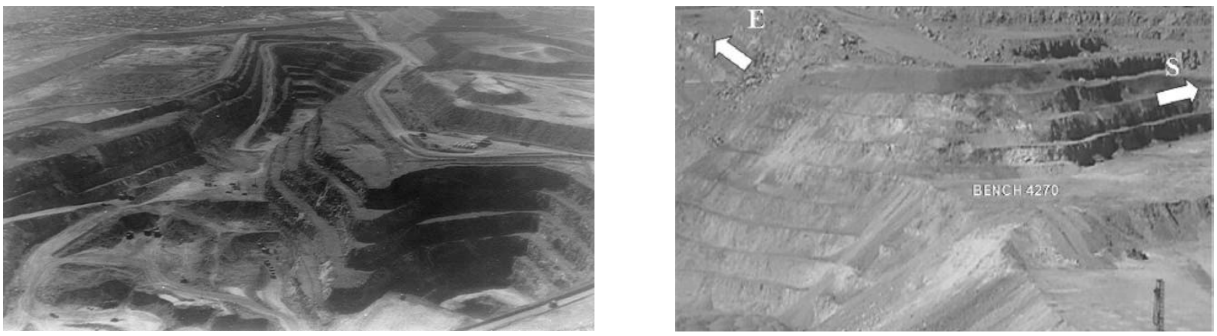
Abstract

Convex geometries in open pits, also known as 'nose' or 'bullnose' slopes, are generally considered sectors with high potential to develop sliding instabilities. Despite this, within the current state of practice, design considerations for these sectors are scarce or limited to certain types of rock mass conditions. Practical experience has shown that the performance of this type of slope geometry heavily relies on the effects of stress redistribution given the slope convexity, the competency of the rock being excavated, the presence of major and minor geological structures as well as operational factors that may include blasting damage. In this light, this paper reviews the technical literature pertaining to geotechnical design considerations for convex and concave slope geometries and presents examples where the effect of deconfinement and the influence of lateral stresses are evaluated through three-dimensional numerical modelling. The effect of convexity (plan curvature) on slope stability is analysed by evaluating 'nose' geometries assuming idealised slope geometries and isotropic homogeneous rock masses with low to medium geotechnical quality.

Keywords: *nose geometry, bullnose, convex slope, lateral stress, deconfinement*

1 Introduction

Convex geometries in open pits, also known as 'nose' or 'bullnose' geometries, are considered zones with high potential for initiating sliding instabilities as a result of loss of confinement. In a mining operation, as shown in Figure 1, 'noses' can result as different phases of mining join together, they also can be found where there are sudden changes in geology such as having hard rock next to a soil-like material (Read & Stacey 2009) or sudden transition in pit slope angles over short lengths. Although convex slopes are relatively common in an open pit, within the current state of practice, geotechnical guidelines to design these unfavourable pit slope sectors are scarce or limited to certain types of rock mass conditions. Practical experience has shown that slope design for this type of geometry is a task that needs to consider that there are aspects that govern the slope performance, these include the effect of stress redistributed within the slope geometry (i.e. lack/loss of lateral confinement), the geotechnical quality of materials and the effect of geological structures. In this light, this paper reviews the technical literature pertaining to slope design for convex slopes and presents idealised examples of convex and concave slopes, where the effect of deconfinement and the influence of lateral stresses are evaluated through numerical modelling in three dimensions.



(a) (b)

Figure 1 Examples of nose geometries. (a) Sandsloot open pit looking north, South Africa (Bye & Bell 2001); (b) nose slope in Ujina open pit, northern Chile (Karzulovic 2004)

The analysis of convex slope geometries is undertaken by evaluating the effect of plan curvature (convex and concave) on stress distribution (presence/reduction of compressive forces/confinement), shear strains, displacement, and Factor of Safety (FoS). A total of nine pit slope geometries, including noses and notches, were evaluated in this paper using this approach. The curvature in these idealised slopes was quantified through the rise-to-chord ratio (curvature ratio), which is ratio of the chord length across the nose to the perpendicular distance from the tip of the nose to the chord as presented in Figure 2.

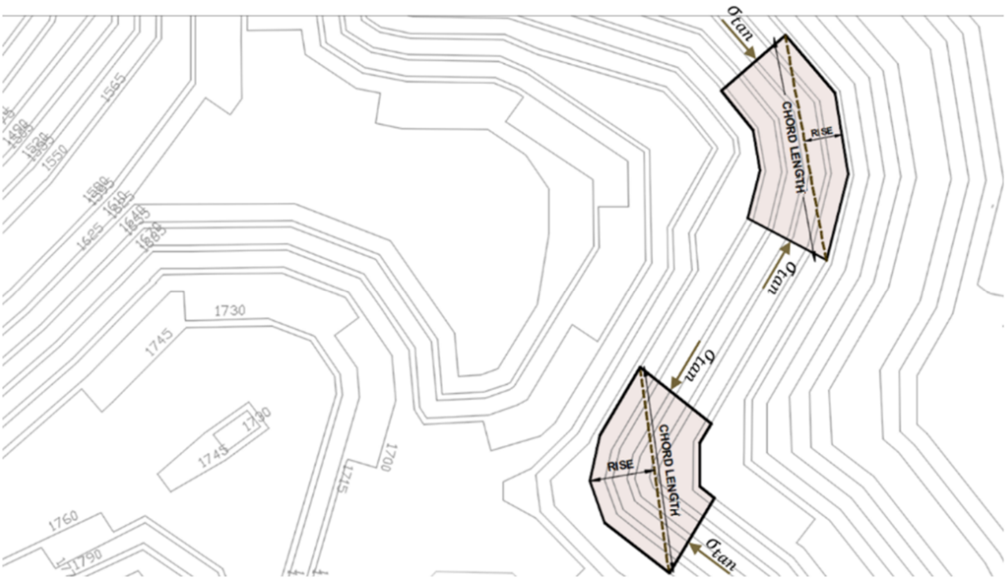


Figure 2 Typical nose and notch geometry showing the ratio of rise-to-chord length (left) and concave slope (right)

As there is evidence that noses represent unfavourable areas with potential stability problems, mine planning is typically required to avoid convex slopes or mitigate the risk by relaxing the pit slope geometry. For an operating mine, detailed geotechnical inspections, comprehensive monitoring, and back-analysis is required to manage this type of slope. Any sign of instability or progressive deformation is required to be reported and included into the stability analysis. An example of nose failure management including a three-dimensional numerical model is presented by Karzulovic (2004), where cracking and loosening of the 'nose' took place as expected without disrupting mining operations. In this case, the author presented how stability assessments predicted that the failure would be too slow to affect mining in the pit.

Accordingly, it can be postulated that inter-ramp slope angles (IRA) need to be designed not only based on the slope height and the geotechnical model, but also dependent upon the plan geometry of the slope due to the lack/presence of lateral confinement (favourable or unfavourable). The failure mode considered in this paper correspond to instabilities predominantly controlled by the quality of the rock mass (Group A) and under the influence of adverse dipping structures non-daylighting at the IRA (Group B). Pure structural failure modes including rock masses with prominent/pervasive structural anisotropy, foliated rock masses or slopes heavily influenced by pore pressures are out of the scope of this work.

2 Background

Different authors, such as Hoek & Bray (1981), highlighted the importance of utilising a three-dimensional approach to analyse the stabilising effect of slope curvature due to lateral restraint for straight and concave slopes (confinement). Piteau & Jennings (1970) studied the influence of plan curvature using limit equilibrium techniques, these authors assessed the stability of existing shale slopes with similar height (around 100 m) in a diamond mine. They found that there was an inversely proportional relationship between the naturally developed overall slope angles and the slope plan radius of curvature, for both concave and convex slopes. This study highlighted that in all analysed cases, smaller radii (concave slopes) gave rise to steeper slopes.

Hoek & Bray (1981) also suggested a design procedure that can be applied under homogeneous geological settings, which was deemed to account for the confinement effect on the slope (favourable or unfavourable) when dealing with concave and convex geometries. The authors highlighted that the driving factor to follow this procedure was based on the ratio between the radius of curvature and the slope height. The suggestion consisted of adding or reducing, according to the type of slope geometry (nose or notch), 10 degrees to the angle obtained by using conventional bidimensional stability analysis. These findings are consistent to more recent studies such as Narendranathan et al. (2013) and Kayesa (2006).

Despite the above, there was no consensus across the revised studies in this paper with respect to the application of the theory postulated by Hoek & Bray (1981). Using two- and three-dimensional numerical modelling, relatively recent studies such as Cala (2007), Lorig & Varona (2007), Wines (2015) or Gomez et al. (2002) obtained a variety of factors of safety for both convex and concave slopes, some of which were higher than those for straight slopes. The majority of these authors concluded that, generally, concave slopes will be more stable than straight slopes. However, Wines (2015) posited that higher factors of safety in convex slopes could be obtained when, for a given failure shape, the failure involves less volume in comparison to a straight slope (i.e. a reduction of the driving forces hence resulting in a higher FoS). As observed, there is an evident discrepancy in the available literature when dealing with convex and concave slopes, especially regarding the effects of slope curvature on slope stability and its quantification. Moreover, it appears that the expected critical unfavourable conditions of convex slopes (e.g. lack of lateral confinement, tensile stresses) have not been clearly represented in previous numerical analysis studies, which were relying mostly on the estimation of factors of safety as the main reference of stability.

Taking into account that rock masses can be considered extremely weak under tensile conditions (Hoek 2016), it is the author's opinion that the stability assessment of convex slopes should always include an analysis of the stress relief/redistribution to locate tensile stress concentrations to complement the estimation of safety factors. These factors, in numerical modelling, are obtained by reducing the slope material(s) strength as described by Dawson et al. (1999) until slope failure is reached, which might not necessarily represent the performance of a convex rock slope. It is therefore the objective of this paper to show the value of assessing stress concentrations throughout the slope geometry, so that lack of lateral confinement can be better understood to complement typical estimations of factors of safety when designing noses.

2.1 In situ stresses

In current practice, it is usually assumed that concave slopes are more stable than convex slopes as per previously discussed and postulated by different authors. This assumption is based on the lack of confinement in noses and the beneficial effects of confinement in concave slopes. Noses are generally considered as unfavourable areas with the potential to develop stability problems (Narendranathan et al. 2013) and susceptible to the influence of in situ stresses. As presented by Azocar & Hazzard (2015), concave slopes located in stress environments with a *k* value (ratio between the in situ horizontal and vertical stress) of 0.5 produced lower factors of safety when compared to similar models with a *k* value of 1.0. This observation is consistent with previous work, a reduction in the horizontal stress results in a decrease of the stress confinement, and hence a lower rock mass peak shear strength can be expected. In other words, given the premise that rock mass conditions are the same, a reduction in the *k* value results in an increment of the driving force relative to the resisting force (confinement). This behaviour was also observed by Xing (1988) using limit equilibrium analysis. However, more recently, considering *k* values of 1.0, 3.0 and 0.5, Wines (2015) studied three-dimensional slope models using 3DEC and no significant effect of the in situ stresses on the factors of safety was found for concave and convex slopes. The difference in the estimated factors of safety was around 0.05 across different stress conditions, which can be considered negligible for practical purposes. Potential aspects influencing these counter-intuitive results might include low values of radii of curvature (10–60 m) being applied to convex slopes resulting in smaller bullnoses, use of linear constitutive models or non-representative strength parameters, among others.

2.2 Rock mass tensile strength

It should be recognised that rock masses tend to be very strong in compression while extremely weak, or even zero strength, under tension (Hoek 2016). In fact, as highlighted by Sjoberg (1997), for low confining stresses (pit slope environment), the available rock mass strength criteria (e.g. Hoek–Brown failure criterion 2002 as defined by Hoek et al. 2002) assumes that the tensile strength is generally low, if not zero as presented in Figure 3. Mohr–Coulomb failure criterion aligns with this assumption as the tensile strength is usually obtained by specifying a cutoff tension for the failure envelope, owing to the lack of physical meaning of this criterion when normal stresses are negative.

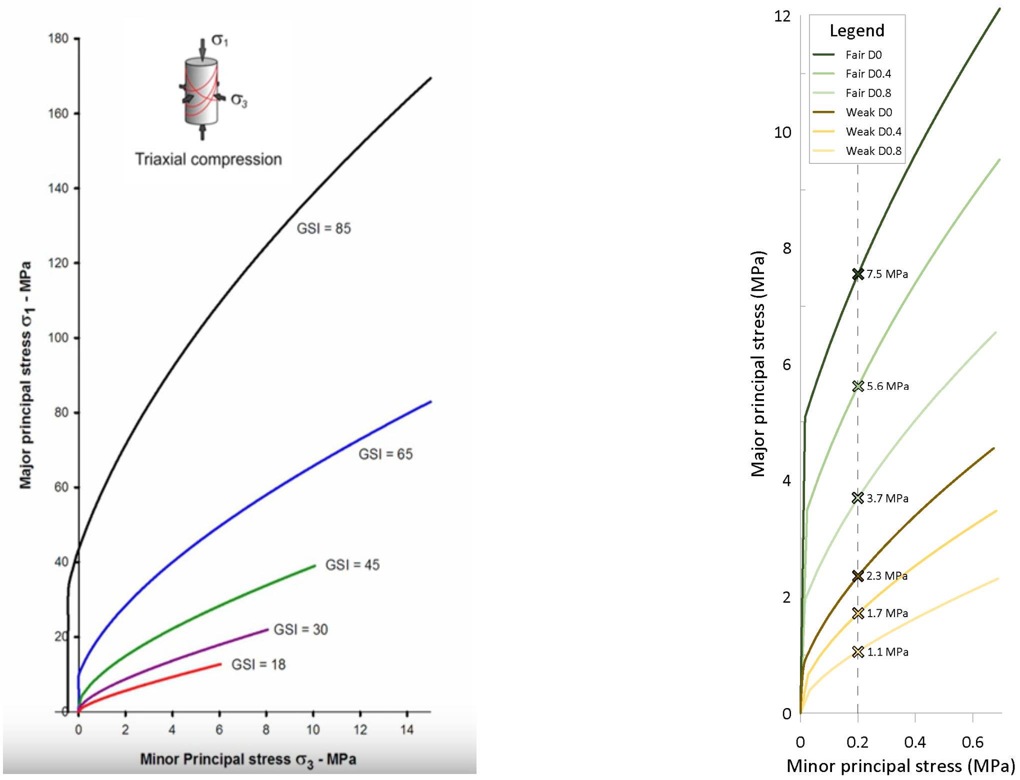


Figure 3 Non-linear failure envelope for rock masses. (a) Hoek–Brown failure criterion (Hoek et al. 2002) for different ranges of geological strength index (GSI) values, showing no tensile strength for lesser GSI values than 65. (b) Failure envelopes for weak and fair rock masses being modelled in this paper, see Section 3.2

The behaviour described above is typically applied to granular materials or rock masses without any interlocking. Nevertheless, for competent isotropic rock masses with multiple joints providing some interlocking of blocks, it might be adequate to consider that a small tensile strength can be transferred through the rock mass; despite of this, in practice it is commonly adopted that rock masses have zero tensile strength. Consistent with a practical perspective, the rock masses were modelled assuming no tensile strength.

3 Slope stability and stresses analysis

In current practice, it is generally accepted to start assessing the stability of pit slopes utilising two-dimensional approaches assuming plane strain conditions (i.e. slice of an infinitely long slope). Within this approach, slope plan geometry or stress rearrangement surrounding slopes is generally not part of the assessment. Moreover, practical evidence suggests that convex slopes, especially those with low values of radii of curvature (high rise-to-chord ratios), are considered unfavourable areas with the inherent risk to develop stability issues. These issues in noses might be exacerbated by pore pressures and blast energy, with this latter aspect being a contributing factor rather than a cause. Also, blast damage may be exacerbated by reduced confinement in convex slopes, allowing for further loosening of rock blocks. Site observations support that blasting conditions (blast energy and gas pressure) influence nose stability as this type of energy propagate preferentially along planes of weakness. The implementation of pre-split and associated careful trim blasting as well as an adequate pattern design and sequencing generally results in diminishing excessive energy being propagated into the nose wall.

Failure mechanism typically involves the appearance of tensile cracking around the 'nose' and crest, and in some cases, with subsequent small-scale planar and wedge failure, which might be good indication of major deep-seated instability. Although small-scale failures are not necessarily the cause of major failures, these are considered good indicatives of slope instability. Nose failures can be associated to the lack of confinement within the slope, which, depending on the stress regime and slope geometry, might cause tension in different sectors of the nose. This paper is intended to provide an analysis of nose geometries where the confinement is investigated using three-dimensional models. The analysis evaluates how idealised slopes with different rise-to-chord ratios are affected/influenced by the lack/presence of deconfinement/confinement. This is primarily assessed by analysing the stress distribution due to plan geometry (ratio rise/chord in Figure 2).

3.1 Tangential stress

As noted by Piteau & Jennings (1974), Long et al. (1966) proposed the idea of the development of a concentration of tangential stresses in the boundary of any open pit as a function of the redistributed horizontal component of the stress field. This horizontal component is produced by the lateral constrain of rock mass load by the overlying material, by tectonic forces, or by both. The horizontal stress is normally estimated as a fraction of the vertical stress (i.e. the weight of the vertical column of rock).

According to the mentioned authors, the tangential stress concentrations could be either compressive or tensile depending upon slope geometry and the horizontal stress field. The favourable compressive conditions are found in concave slope geometries (notches), while an unfavourable stress regime with less confinement, and sometimes comprised of tensile stresses, can be expected in noses. A summary describing these field stresses is presented in Table 1, which should be read in conjunction with Figure 4. Note that for the concave slope case, there is an arch-like beneficial effect produced by the tangential stress.

Table 1 Stress field expected in noses (convex slopes) and notches (concave slopes)

Parameter	Concave	Convex
Stress effect	Strengthening	Weakening
Field stress along the slope face	Compressive stresses in all directions generating a cohesion-like strength resulting in a greater shear strength due to more confinement	Cohesion-like strength is reduced, tensile stress concentration (σ_3) induce instability in unrestrained blocks
Rock mass condition at the face	Interlocking blocks tend to be squeezed	Interlocking blocks show loss of confinement or experience tensile stresses and can ravel
Tangential stress – minimum principal stress (σ_3)	Compressive/beneficial, acting in radial direction	Tensile/unfavourable, acting in a direction tangent to the slope

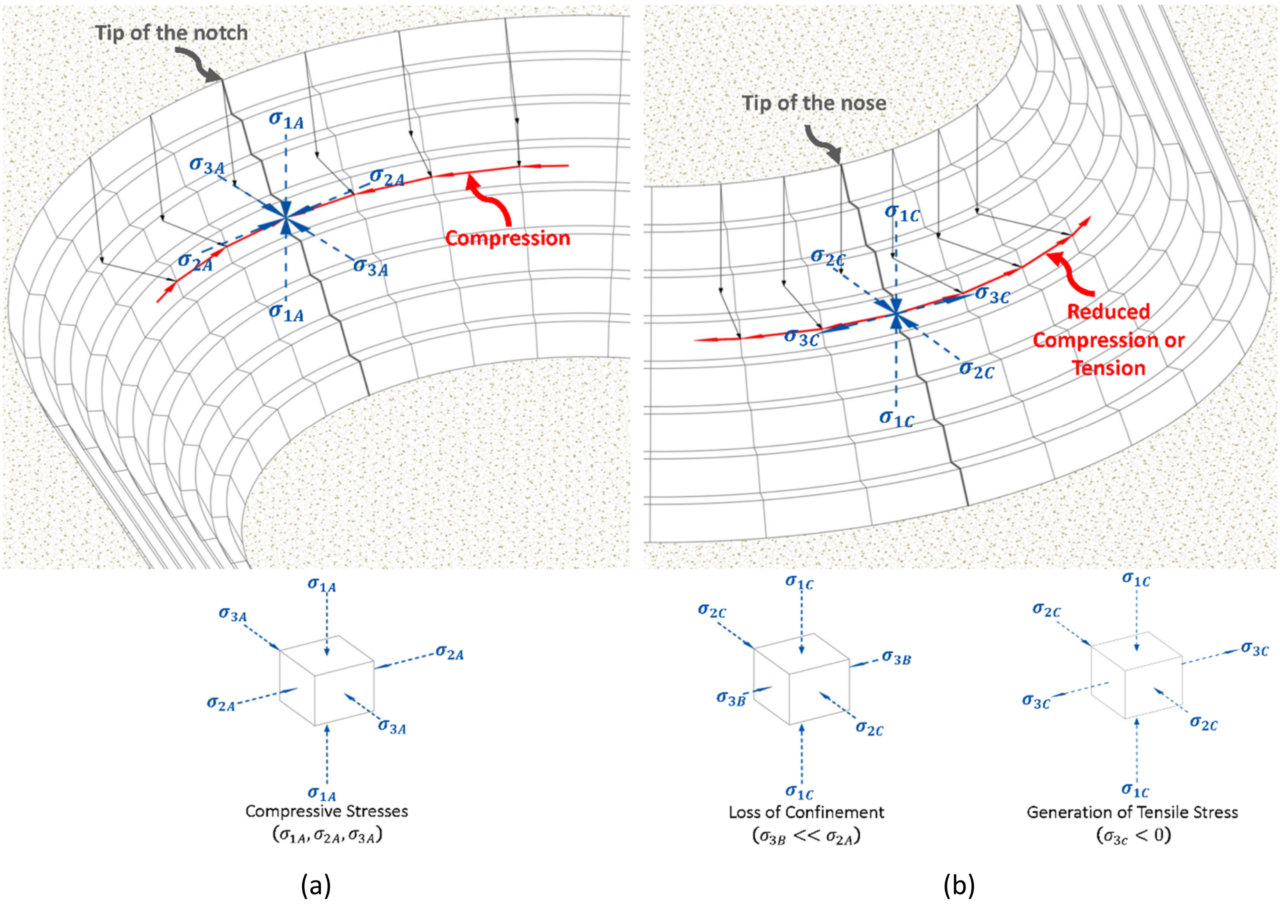


Figure 4 Expected field stress. (a) Concave slope where the in situ stress is governed by confinement; (b) Convex slopes where confinement is reduced, this geometry is also likely to generate tensile stresses (modified after Piteau 1974)

3.2 Concave and convex slope stability

To investigate the stress distributions in concave and convex slope geometries, a series of three-dimensional numerical models were analysed using the computer code RS3 (Rocscience 2023a). Examples of the RS3 slope models are shown in Figure 5. Given the importance of stress redistribution, due to the excavation process, for the purposes of this paper, the modelled mining sequence adopted a total of 10 stages prior to reach the final slope geometry. The modelled slope geometries (noses and notches) are illustrated in Figure 6, where the rise-to-chord ratio for each model is also indicated to quantify curvature. In general, all slope models consisted of a 120 m height slope, comprised of 15 m height benches, with a 46º IRA. The simulation was performed with 1:1 horizontal to vertical pre-mining stress ratios. It is worth noting that sensitivity to pre-mining in situ stress was not considered in this assessment.

The rock masses were represented using a perfectly plastic material model with the properties shown in Table 2; as indicated in Section 2.2, no tensile strength was considered. The material failure envelopes for Case 1 and Case 2 are shown in Figure 3. The isotropic rock masses were modelled using the generalised Hoek–Brown failure criterion (Hoek et al. 2002), which introduced the disturbance factor (D) to reduce the rock mass strength due to effects of blasting and stress relief. As shown in Figure 6, a zoned D-factor modelling approach was considered in all models, which defined constant D-values of 0.8, 0.4 and 0.0 for depth intervals of 0–12, 12–24 and >24 m, respectively. As the guidelines provided for the selection of D are not specific for convex or concave areas, the same D-approach (i.e. similar zones and D-values) was implemented for both noses and notches.

Table 2 Rock mass properties

Parameter	Group A (slopes controlled by the quality of the rock mass)		Group B (slopes with adverse dipping structures)	
	Case 1 Weak isotropic RM*	Case 2 Fair isotropic RM	Case 3 Weak dominantly structural RM	Case 4 Fair dominantly structural RM
Constitutive model	Hoek–Brown	Hoek–Brown	Generalised anisotropic model	Generalised anisotropic model
Unit weight (KN/m^3)	25	25	25	25
Poisson's ratio	0.25	0.25	0.25	0.25
GSI**	30	50	–	–
m_i**	8	12	–	–
Sigc$_i$**(Mpa)	40	80	40	80
Young's modulus Ei (Gpa)	15	30	15	30
DJS*** – persistance (%)	–	–	85	85
DJS – Dip (°)	–	–	60	60
DJS – DipDir (°)	–	–	Parallel to straight slope	Parallel to straight slope
DJS – Mohr–Coulomb parameters****	c = 10 kPa Ø = 25°		c = 10 kPa Ø = 25°	

Notes: (*) RM: rock mass, (**) Hoek–Brown criterion parameters, (***) DJS: D = dominant joint set non-daylighting at the inter-ramp angle, (****) c = cohesion of kPa, and Ø = friction angle.

The analysis methodology adopted in this paper is consistent with the slope stability evaluations carried out by Hoek et al. (2009). The input rock mass properties are, in general, weaker, and relatively more deformable in comparison to parameters expected for hard rock mines. Nonetheless, it is considered that this set of parameters will not only show how weak to fair rock masses behave in concave/convex slopes, but also facilitate the identification of areas with drastic changes in in situ stress.

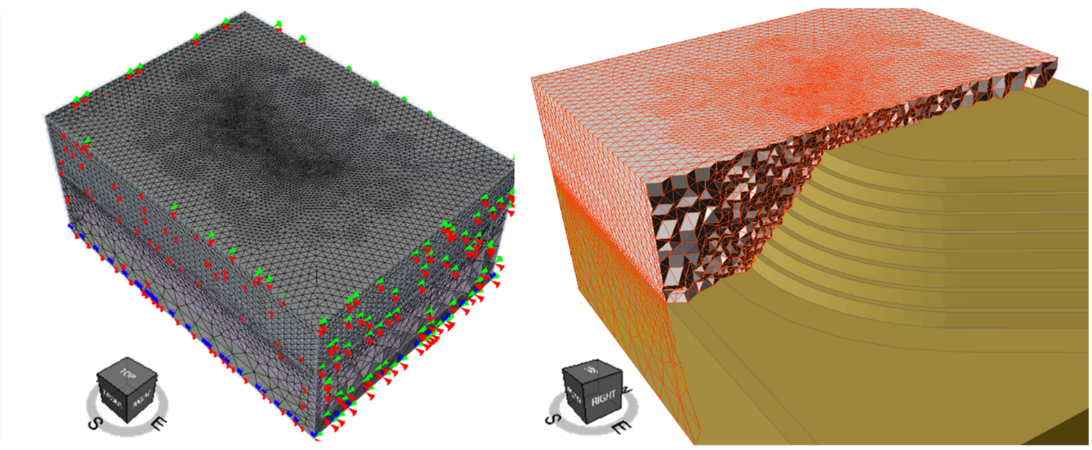


Figure 5 Example of RS3 nose model for a geometry with a curvature ratio of 0.25

Using the strength reduction method implemented in RS3, FoS was calculated for the critical overall shearing surface on each three-dimensional model. Similarly, the two-dimensional slope configuration (i.e. plane strain) for slopes 1 to 9 was assessed using the numerical modelling software RS2 (Rocscience 2023b). The results for all cases, including 3D and 2D modelling, are shown in Figure 7. Consistent with previous studies, results from all cases (Group A and Group B) are presented showing the relation between the normalised FoS (FoS obtained for the 3D models divided by the FoS for a plane strain analysis), and the rise-to-chord ratio.

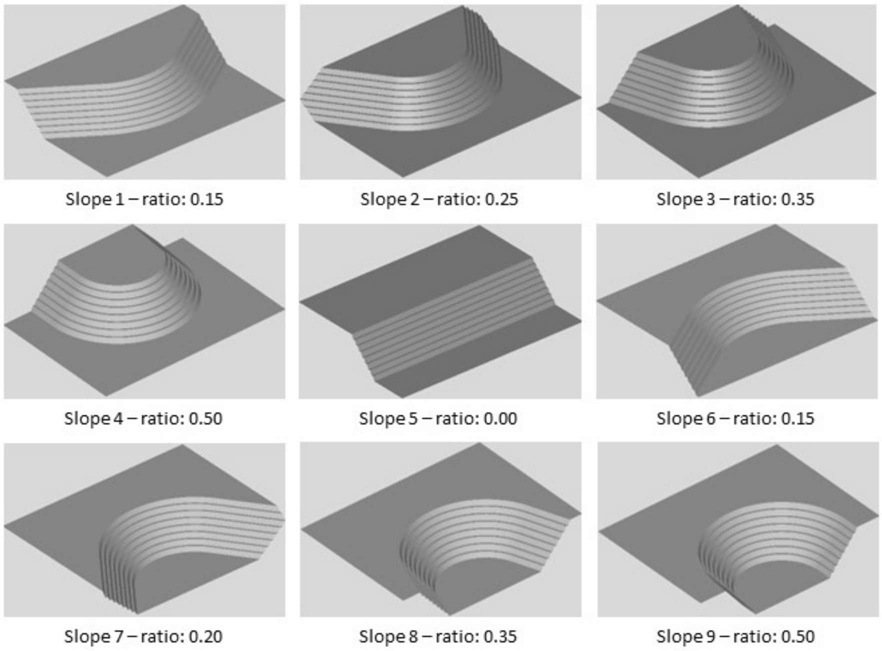


Figure 6 Slope geometries modelled in RS3, quantifying curvature by using the rise-to-chord ratio (curvature ratio)

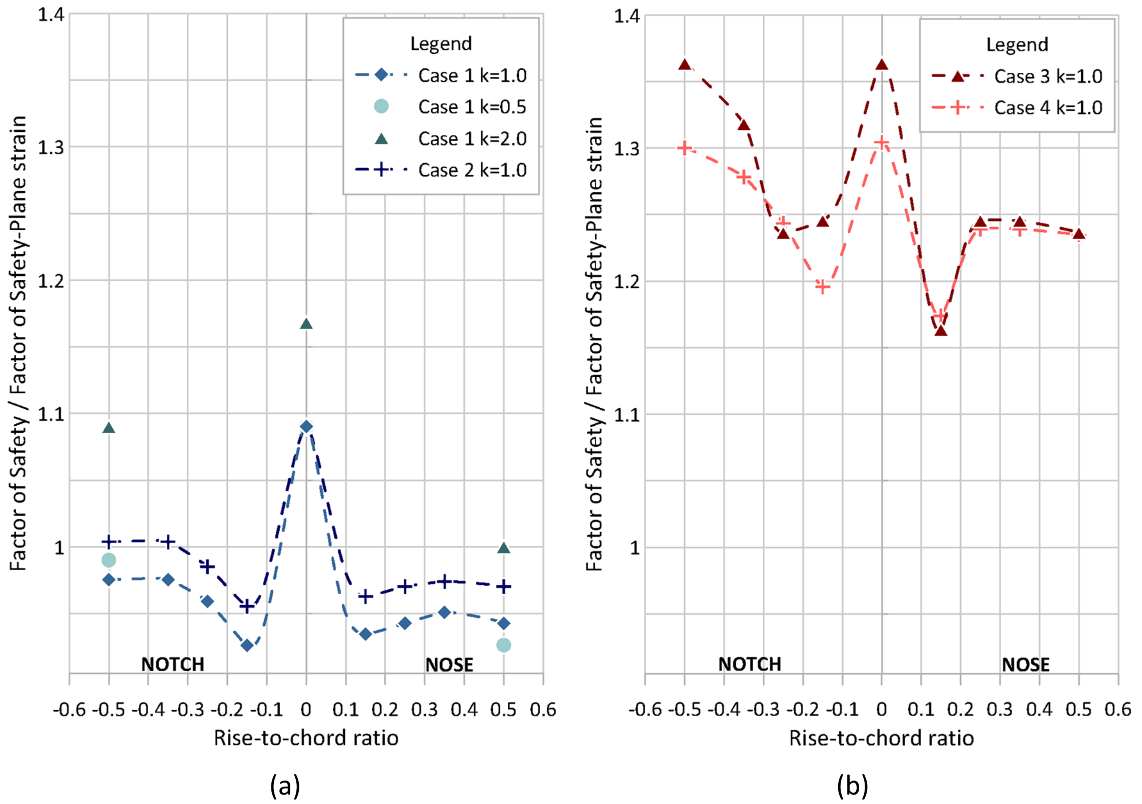


Figure 7 Estimated factors of safety for slopes 1 – 9. (a) Case 1 and Case 2; (b) Case 3 and Case 4

Based on results obtained, the following can be commented:

- FoS for two-dimensional models were lower when compared to equivalent three-dimensional straight slopes, around 10% and 30% for isotropic and anisotropic cases respectively.
- Consistent with Piteau & Jennings (1970), in all evaluated cases an inversely proportional relationship between the FoS and the rise-to-chord ratios was observed for convex slopes. For concave slopes in weak rock mass, FoS was marginally higher for slopes with high ratios. In concave slopes where anisotropy was considered, the improvement on stability for slopes with high ratios was significant. Results suggest that the effect of slope curvature on stability for convex slopes is less than far for concave slopes.
- In Case 3 and 4 where anisotropy was considered (rock masses with fairly adverse structural orientation), the FoS is generally slightly lower in comparison with results from the isotropic cases (Case 1 and 2). Despite this slight difference, it is worth noting that critical failure surfaces in isotropic cases for convex slopes involved less volume and were constrained to the upper benches only when compared to anisotropic cases, which involved a deep-seated failure (i.e. planar failure with rock mass breakout at the toe). This potentially caused that FoS for convex slopes in a few cases with anisotropy was marginally higher when compared to equivalent isotropic cases.
- FoS for concave slopes is slightly higher than those for convex slopes, confinement provided by this type of geometry improved, in general, the stability conditions (deformations). The non-substantial difference in FoS values can be attributed to the influence of same D-values/zones assigned for both convex and concave slopes.
- FoS for convex slopes is marginally lower than those for concave slopes. Aspects to understand this might include: (a) Similar D-approach assigned for both concave and convex slopes, which could be misrepresenting the stress rearrangement expected for convex slopes. (b) results are mainly reflecting failure after reducing the compressive strength only (i.e. deconfinement), these are independent from tensile stress concentrations and rock mass tensile strength.
- For convex geometries, critical failure surfaces were generally located in the vicinity of the nose tip, while for concave geometries, failure was observed to develop in the transition area between the slope curvature and the straight slope. Failure in convex slopes generally involved less volume when compared to straight o concave slopes.
- Supplementary review of results is required to understand the effect of lateral confinement and slope curvature (rise-to-chord ratio) for convex slopes as this type of geometry typically fails under tension conditions. Characterising the distribution of yielded elements to estimate rock mass disturbance is key to complement FoS estimations, this should include a quantification of the number of yielded elements in the slope that has occurred as a result of lack of confinement. Modelling results showed that for convex slopes, the tangential stress appear to diminish in a direction from the toe to the crest of the slope, the rate being greater for slopes with higher curvature ratios.
- Sensitivity analysis on the effect of the D-factor showed that the FoS is significantly sensitive to changes in D-values for rise-to-chord ratios greater than 0.35. This finding suggests that for the modelled rock mass type, this type of geometry should be avoided.
- Obtained results suggest that slope angles (IRA) need to be designed not only based on the slope height and the geotechnical model, but also dependent upon the plan geometry of the slope due to the lack/presence of lateral confinement (favourable or unfavourable).
- Results generally showed that effect of in situ stress ratios and D-values play a significant role on the slope performance of both concave and convex slopes. This aspect is discussed in more detailed in Section 4. As there is still uncertainty around the effects of D-zonation in the analysis, an option to mitigate misleading results when designing convex slopes is to use guidelines that characterise the D-factor based on the effect of confinement, such as the methodology developed by Rose et al. (2018).

4 Stress distribution

Results showed that stress deconfinement and the extent and magnitude of tensile stress concentration are different on each analysed slope as shown in Figures 8–10. Even though in situ stress apparently does not have a major influence in stability, tensile stresses within the geometries start to be significant and influencing the extent of the critical failure surface (tending to be deep seated) with rise-to-chord ratios higher than 0.25. This is illustrated in Figure 11, where it can also be observed that for slopes with ratios lower than 0.25, the estimated maximum compressive stress is considerably high. This can be understood as a direct influence of the favourable confinement condition for concave and straight slopes.

Accordingly, it can be postulated that convex slopes with ratios higher than 0.3 tend to develop unfavourable tensile stresses that can lead to slope relaxation and corresponding excessive slope deformation. It is then recommended to avoid type of nose geometries, or alternatively a change in the slope design (height or angle) might be considered while evaluating the mining sequence impacting deconfinement.

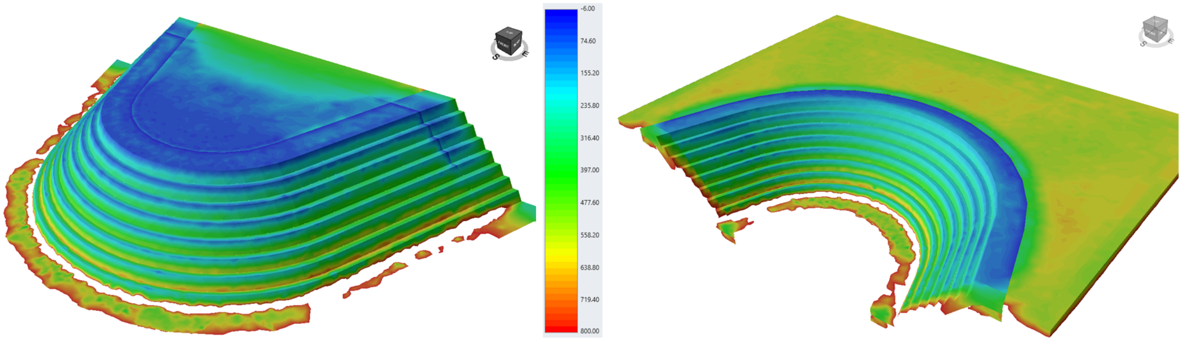


Figure 8 Major stress concentration in the exterior contour for Slope 3 and Slope 8 (rise-to-chord ratio = 0.35)

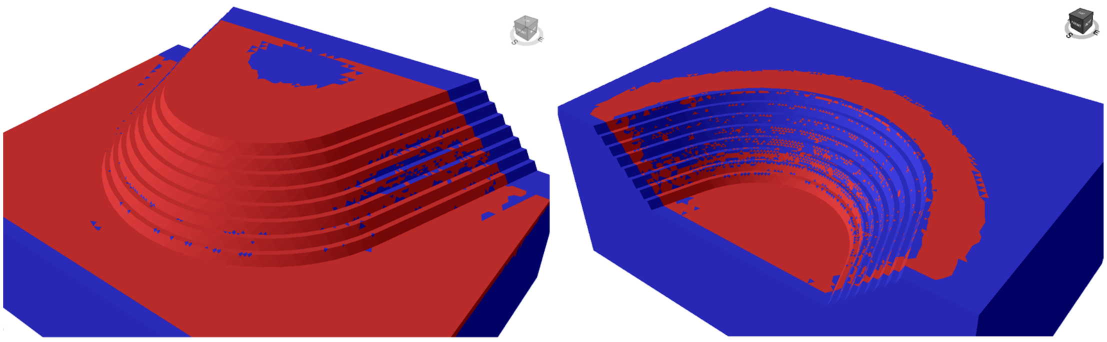


Figure 9 Distribution of yielded elements in the exterior contour for Slope 3 and Slope 8 (rise-to-chord ratio =0.35)

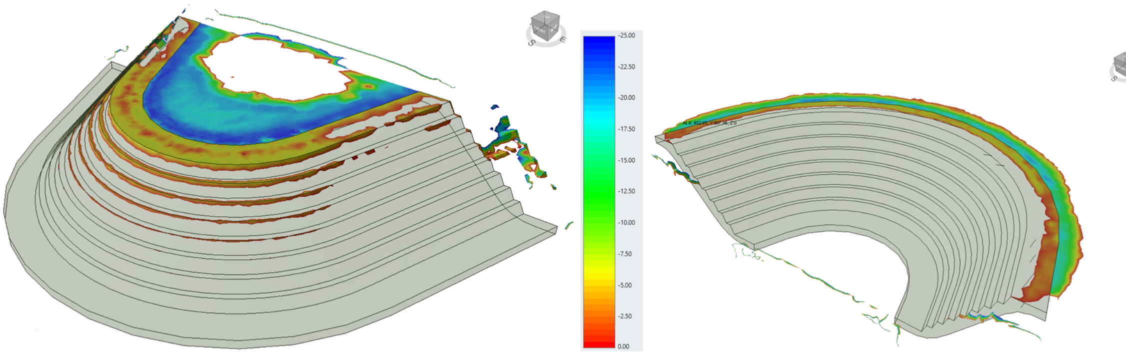


Figure 10 Tensile stress concentration in the exterior contour for Slope 3 and Slope 8 (rise-to-chord ratio = 0.35)

Based on the analysis results, the following can be concluded:

- Consistent with the tangential stress theory postulated by Long et al. (1966), stress redistribution causing loss of confinement, and, in some cases, generation of zones subjected to tensile conditions, was observed in all nose models.
- In concave geometries (slopes 1 to 4), compressive circumferential stresses were formed, which constrains and tend to stabilise the slope. Results showed that for the weak rock mases, this lateral constrain provided by the slope curvature is greatest at the toe.
- In convex geometries, due to the lack of constraint/confinement, there is a potential for the slope to bulge. As observed in strain contours, bulging is likely to begin at 15% of the slope above the toe for noses with high curvature ratios.
- For convex slope models (isotropic and anisotropic cases) with high curvature ratios, zones that experienced high tensile stress concentrations and contain yielded elements under tension are commonly located at the slope crest and within the exterior of the upper side of the slope. This observation is consistent with sectors where cracking is typically found in practice. The overall slope might undergo under tensional failure if this condition is exacerbated by rainfall or blasting effects.
- Results for the convex slopes are very sensitive to the D-approach (values and extent) utilised for modelling. The number of yielding elements within the slope face is heavily impacted by the assigned D value (Figure 9); accordingly, the critical deep-seated surfaces are manifesting influence by the extend of the D-zone, these were observed to be located between the D=0.8 and D=0.4 zones.

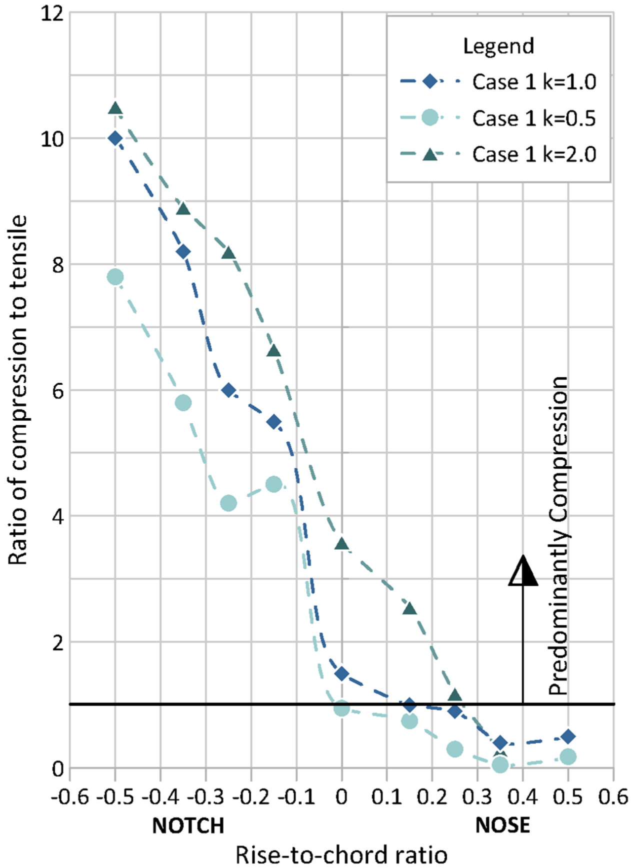


Figure 11 Example of stress concentration analysis for Slopes 1 – 9 in cases where the rock mass was modelled isotropic (Case 1)

- In situ stresses were observed to have a significant influence in the FoS obtained for concave slopes and convex slopes. Modelling results using *k* values of 0.5, 1.0 and 2.0 suggest that the rate of loss of confinement in noses is directly related to in situ stresses (convex destressing); in other words, the stress regime play a significant role in the stress deconfinement and generation of tensile stress concentrations and the resulting FoS. The higher the *k* value, the less susceptible is the slope to both loose confinement and generate tensile stresses (Figure 11). These findings are consistent with Long et al. (1966), these authors postulated that the tangential stress concentration on the boundary of an open pit develop as a function of the horizontal component of the stress field.
- The analysis of tangential stress concentration showed that convex slopes with curvature ratios (rise-to-chord) higher than 0.25 developed tensile stress concentrations that influence the resulting FoS. Two-dimensional modelling might need to be complemented with three-dimensional modelling this type of nose geometry. Conversely, even a small amount of confinement (ratios lower than 0.25) in convex slopes results in a significant increase in FoS.

5 Conclusion

Experience in open pit mining has shown that nose geometries are inherently more unstable than concave slopes. Plan radii and associated curvature as well as stress regime play a significant role on the slope performance, especially for convex slopes. Results from convex slopes showed that there is an inversely proportional relationship between high curvature ratios are FoS. Consistent with the concept of tangential stress, nose models in all cases (weak and fair rock mass) exhibited a significant reduction of confinement and, in some cases with high curvature ratios, areas under tensile stresses were observed. The concentration of tensile stresses tends to develop over the slope face, near the toe and the upper side of the slope.

For convex slopes, modelling results showed that the estimation of FoS need to be complemented with an evaluation of stress concentration for slope design purposes. This evaluation is required to study the effect/loss of lateral confinement and slope curvature on slope stability. Modelling results support the practical evidence that failure in convex slopes is heavily influenced by stress deconfinement, results also showed that convex slopes with high curvature ratios tend to generate tensile stresses, exacerbating instability. The analysis of tangential stress concentration showed that convex slopes with curvature ratios (rise-to-chord) higher than 0.25 developed tensile stress concentrations that influencing the resulting FoS. Two-dimensional modelling might need to be complemented with three-dimensional modelling this type of nose geometry. Conversely, even a small amount of confinement in convex slopes results in a significant increase in FoS.

The in situ stress plays a significant role in the stress deconfinement (loss of confinement) and generation of tensile stress concentrations and the resulting FoS for convex slopes. The higher the *k* value, the less susceptible is the slope to both loose confinement and generate tensile stresses. Results were also found to be very sensitive to the D-approach definition. From a designer perspective, an option to mitigate misleading results when assessing convex slopes is to select D-values using guidelines that consider the effect of confinement, such as the methodology developed by Rose et al. (2018). When performing stability analysis, the slope design workflow should account for the assignment of different D-values for convex slope geometries based on the curvature ratio, especially when this ratio is higher than 0.25.

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