Tensile crack zone consideration in stability analysis of slopes using Slide

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ABSTRACT
In geotechnical engineering, slope stability analysis is a common practice. In this paper, a numerical code from Rocscience, called Slide, is used for stability analysis of slopes under fully drained or dry conditions. Particular attention is paid to the influence of tension cracks on the stability of slopes. Tension cracks are frequently observed behind the crest of slopes in open pit mines. They have for effect to weaken the slope walls and reduce the stability of slopes. In limit equilibrium numerical modeling, tension crack zones can be identified by examining interslice forces. Once identified, they can be introduced in the new model to update the factor of safety calculation. For most cases, introducing a tension crack zone in the numerical model leads to a reduction of factor of safety. This corresponds well to what is expected. However, the introduction of the identified crack zone in the numerical model may also lead to an increase in the calculated factor of safety in some cases. Project designs based on such type of numerical simulations would not be conservative. Numerical simulation correction is required to obtain more conservative results. Further comparison between the commonly used Hoek-Bray empirical chart method and the numerical simulations indicated that the former method is not always conservative when a zone of tension cracks is present.

RÉSUMÉ
L'analyse de stabilité des pentes est une pratique couramment rencontrée en géotechnique. Dans cet article, un code numérique de Rocscience, appelé Slide, est utilisé pour l'analyse de stabilité des pentes en conditions drainées ou sèches. L'attention particulière est apportée à l'influence des fissures en traction sur la stabilité des pentes. Des fissures en traction sont fréquement observées sur les crêtes des pentes des mines à ciel ouvert. Elles ont l'effet de affaiblir les murs des pentes et de réduire la stabilité des pentes. Dans les modélisations numériques, la zone de fissures en traction peut être identifiée en vérifiant les forces internes entre les tranches verticales. Une fois identifiées, elles peuvent être intrdoduites dans le modèle pour refaire le calcul de facteur de sécurité. Pour la plupart des cases, l'introduction de cette zone de fissures en traction dans le modèle numérique résulte à une diminution du facteur de sécurité. Cela correspond bien aux résultats attendus. Or, l'introduction de la zone de fissures de traction pourrait aussi mener à une augmentation du facteur de sécurité dans certains cases. Une conception de projet à partir de ce genre de résultats numériques ne serait pas conservatrice. Des corrections sont nécessaires pour obtenir des résultats plus conservateurs. En plus, des comparaisons entre la méthode empirique de Hoek-Bray et des simulations numériques montrent que la première méthode ne donne pas toujours des solutions conservatrices lorsque des fissures en traction apparaissent.

1 INTRODUCTION

Stability analysis of slopes is a common practice in geotechnical engineering (Hoek 1970; Panet and Rotheval 1976; Audric and Cojean 1978; Hoek and Bray 1981; Wyllie et al. 2004). It is closely related to the safety and economic feasibility of a project. If the project is to construct a dam, an increase in slope angle means a significant reduction in requirement of land dimension and backfill materials. This, in turn, significantly reduces energy consummation and environmental impact for backfill material transport. However, increasing the slope angle also means a reduction in slope stability conditions, which are usually quantified by a factor of safety (FS). The influence of slope angle on the economic feasibility and stability of a dam or an open pit mine project is schematically shown in Figure 1.

For the case of an open pit mine, the first concern is to determine the optimal slope angle. As indicated in Figure 1, with a steeper slope, the required stripping can be largely reduced, leading to a much smaller stripping ratio, which is defined as the percentage of the stripped waste to mined ore. From an economic point of view, the project would become more profitable with a steeper slope. In addition, a decrease of stripping ratio with an increase of slope angle also significantly reduces the quantity of waste disposal on surface and environmental impacts from the mining industry. However, the slope stability declines with an increase of slope angle. The optimal slope angle corresponds to the maximal but stable slope angle. Determination of such an optimal slope angle requires a detailed stability analysis.

This is, however, a quite complicated issue as the stability of slopes is related to a number of influencing factors, such as mechanical properties of the slope materials, water conditions, dynamic load, slope geometry and so on (e.g., Hoek 1970; Hagan 1978; Hoek and Bray 1981; Sassa 1985; Cojean and Fleurisson 1990). For the case of open pit mines, other factors such as geological structures, in-situ stresses, blasting techniques, surface loads (waste rock piles, tailing ponds, machinery etc.) may also influence the stability of slopes.

A common practice to analyse the stability of slopes is making use of numerical codes that are based on limit equilibrium analyses (e.g., Fellenius 1936; Janbu 1954; Bishop 1955; Morgenstern and Price 1965; Spencer 1967; Fredlund and Krahn 1977; Fredlund et al. 1981). For open pit mines, empirical chart method (Hoek and Bray 1981) is also commonly used when the slope geometry is regular and simple. For most cases, numerical modeling is required due to irregular slope geometry or complex ground conditions.

It should be mentioned that there exist a number of commercialized codes based on limit equilibrium analyses over the world. In Canada, the most used are Slope/W (Geo-Slope 2008) and Slide (Rocscience 2006). Each has its merit and limitation with respect to their cost and technical capability. Here, it is not the authors' intention to evaluate these numerical codes or make comparison between them.

In the following, Rocscience's numerical code Slide is used in slope stability analysis of open pit mines. Particular attention is paid to the treatment of tensile crack zone at crest of slopes. It will be shown that the consideration of potential tensile crack zones, if not adequately handled, can lead to erroneous results. Here, only fully drained or dry slopes are considered. These are common situations in arid regions.

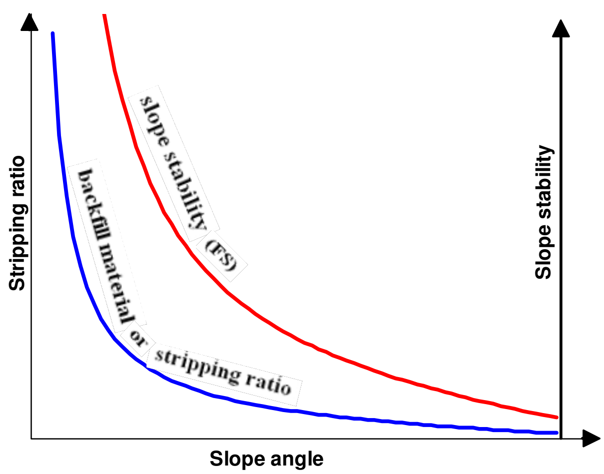

Figure 1. Schematic presentation of the influence of slope angle on the economic issue and slope stability.

2 TENSION CRACKS AT CREST OF SLOPES

In practice, tensile cracks are frequently observed at the crest of slope, especially when the open pit is deep and the slope is steep (e.g., Hoek and Bray 1981; Brawner 1997). For soil slopes, tension cracking may take place even though the slope height and angle are not very high (compared to rock slopes) due to low strength of soils in tension (or cohesion).

In open pit mines, tension cracks are usually the result of stress relief from overburden removal (Figure 2). Once tension cracks are generated, the slope stability can be greatly affected, due to:

1) significant reduction of the resisting surface along the potential failure (sliding) surface (Figure 2)
2) interstitial pressure in the cracks (in non arid regions).
3) forming instable wedges with other geological structures.

Thus, tension cracks should be taken into account in stability analyses.

In Canada, tension cracks are particularly critical due to its climate and abundant provision of water from both rain and snow. In summer, water penetrates into the fractures formed of tension cracks and leads to an interstitial pressure. In winter, ice forms in the fractures and exercises an expansion pressure on the walls of factures. This may lead to fracture propagation. Thus, the slope stability condition may become worse and worse with such freeze-thaw cycles over the years.

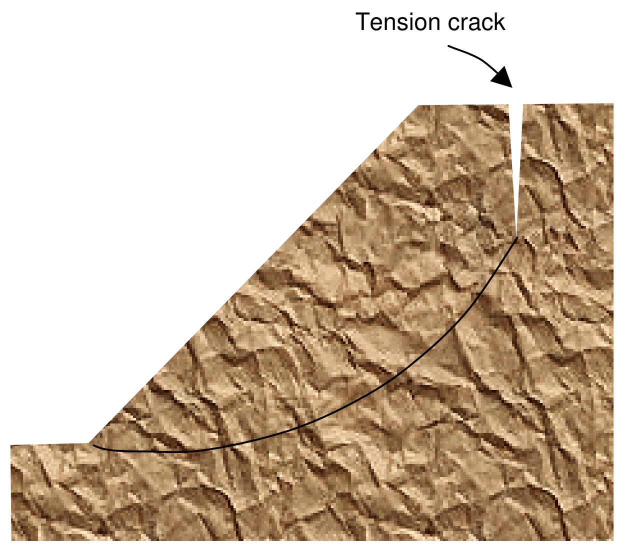

Figure 2. Tension cracks due to stress relief from overburden removal after excavation of the pit (adapted from Hoek 1970).

3 NUMERICAL MODELING WITH SLIDE

In Slide (Rocscience 2006), tension crack zone can be estimated by examining the normal forces between vertical slices. Once a tension crack zone is identified, it should be taken into account in the stability calculation. The slip surfaces will be terminated by the introduced tension crack zone. Tensile stresses in the tension crack zone are removed from the calculations.

For most cases, Slide can give reasonable results as what has been shown in the text manual of Slide. The introduction of tension crack zone leads to a reduction of factor of safety. However, for some cases, the introduction of tension cracks does not always lead to a reduction of factor of safety as shown in the following.

Figure 3 shows a simple slope geometry of 89 m high with an inclination of 70°. The material properties are given in the figure as c = 1.34 MPa and ϕ = 45° (c, cohesion; ϕ, friction angle). The unit weight of the rock mass is $\gamma = 0.027$ MN/m^3. No water was considered in the numerical modeling.

First calculation using Slide with GLE/Morgenstern-Price method (Morgenstern and Price 1965; Fredlund and Krahn 1977; Fredlund et al. 1981) without consideration of tension cracks gave a factor of safety of 3.956 as shown in Figure 4. The GLE/Morgenstern-Price method is based on a general limit equilibrium (GLE) formulation developed by Fredlund and co-workers (Fredlund and Krahn 1977; Fredlund et al. 1981) who make use of an equation proposed by Morgenstern and Price (1965) for the interslice shear forces. Two factors of safety equations are considered, taking into account a range of interslice shear and normal forces related with a characteristic parameter λ and a position function $f(x)$. One equation gives the factor of safety with respect to moment equilibrium, $FS_m(\lambda)$ while the other gives the factor of safety with respect to horizontal force equilibrium, $FS_f(\lambda)$. By imposing $\lambda = 0$, the GLE method reduces to Bishop's simplified method if only the first factor of safety equation is considered or to Janbu's simplified method if only the second factor of safety equation is used. The GLE method reduces to the Morgenstern-Price or Spencer method when both factor of safety equations are considered such that $FS_m(\lambda) = FS_f(\lambda)$. Compared to the simplified Bishop or Janbu method, in which only moment or force equilibrium is considered, GLE/Morgenstern-Price method is physically more representative of slope behavior due to its consideration in both moment and force equilibrium.

Detailed examination of interslice forces revealed that tension cracks take place on slice #21 as shown in Figure 5. Figure 6 shows the new geometry of the model after introduction of the above identified tension crack zone. It is seen that the tension crack zone is very large. This will be addressed in Discussion. Figure 7 shows that the factor of safety is reduced to 2.026 after taking into account the tension crack boundary.

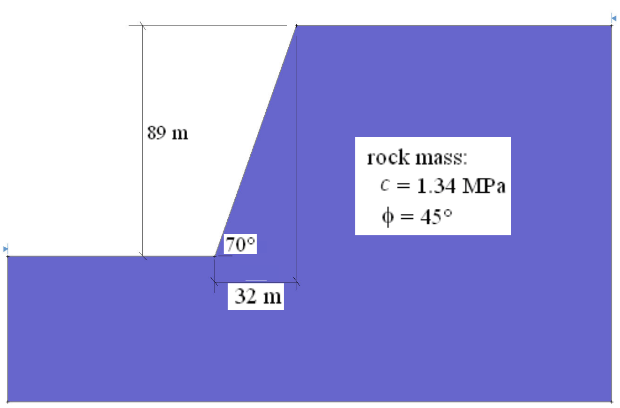

Figure 3. A simple conceptual slope of rock mass.

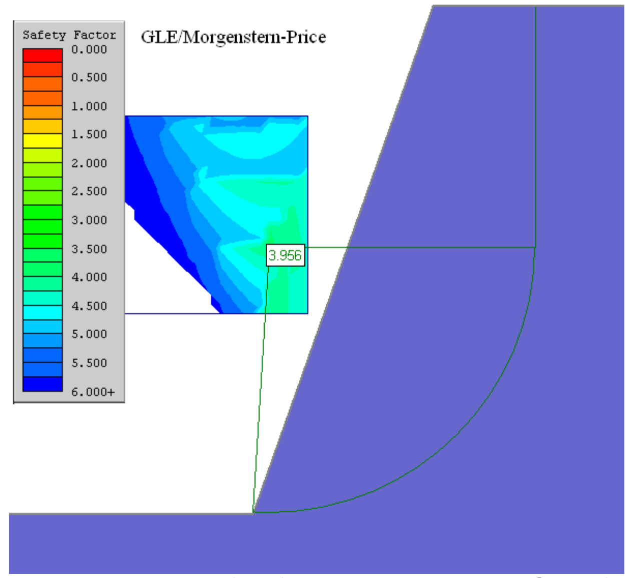

Figure 4. Factor of safety calculated using Slide for geometry given in Figure 3 without consideration of tension crack zone.

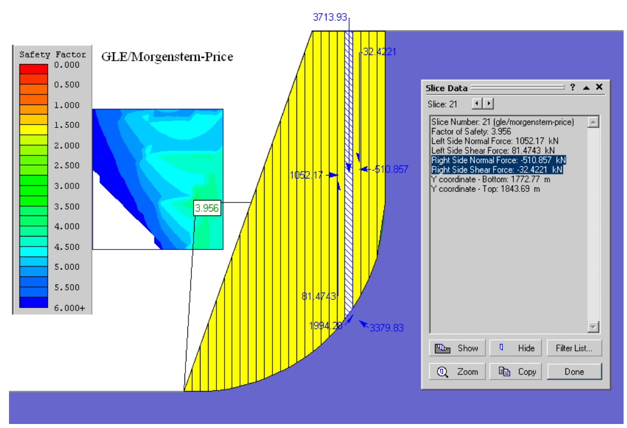

Figure 5. Interslice forces on the critical slice #21.

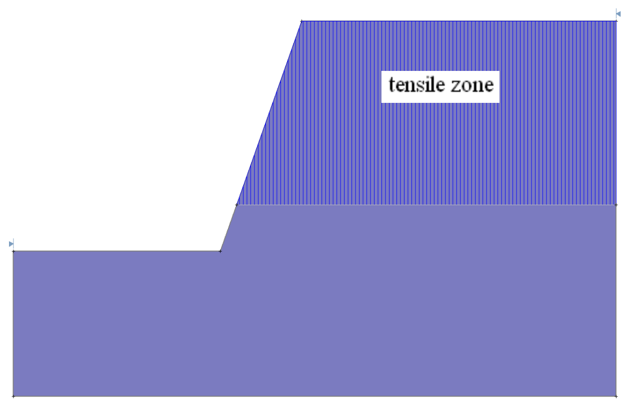

Figure 6. Addition of tensile crack zone at $Y = 1772.77$ m.

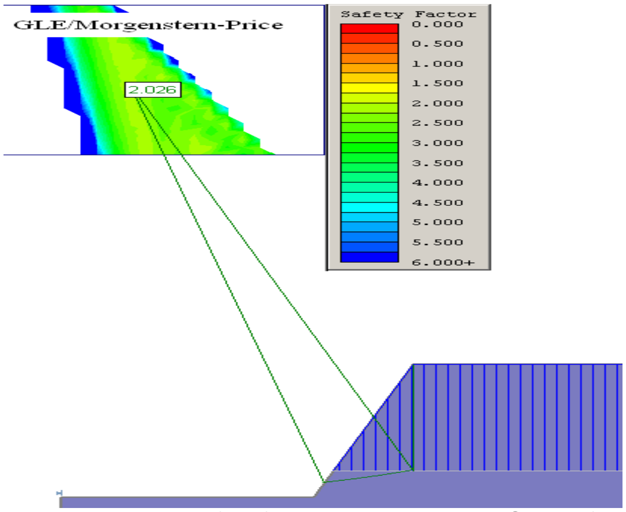

Figure 7. Factor of safety calculated using Slide after introduction of tension crack boundary.

The above sample calculation shows that the introduction of tension crack zone in the numerical model does lead to a reduction of factor of safety. This corresponds well to the expected behavior.

Figure 8 shows another slope of 131 m high with wall inclination of about 70°. The geomechanical properties of the rock masses were shown in the figure, as:

- Rock mass A: *c* = 1.34 MPa, ϕ = 45°
- Rock mass B: *c* = 0.98 MPa, ϕ = 41°
- Rock mass C: *c* = 1.41 MPa, ϕ = 47°.

Again, the unit weight of the rock masses were γ = 0.027 MN/m^3. No water was considered in the numerical modeling.

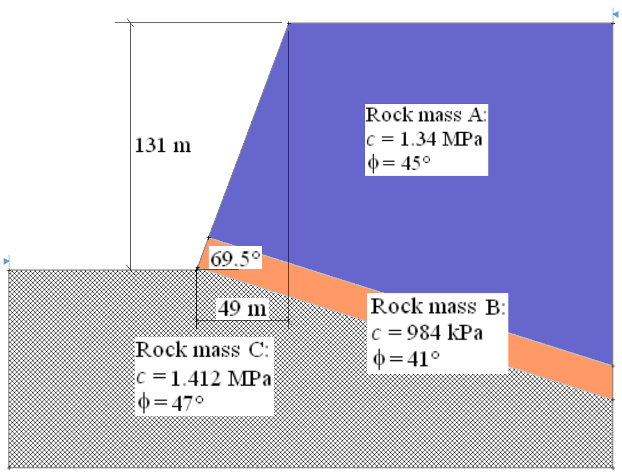

Figure 8. A slope with multiple layers of rock mass in an arid region.

First calculation using the GLE/Morgenstern-Price method gave a factor of safety of 2.86 (Figure 9). Figure 10 shows detailed information of the Slice #42, on which is exercised a compressive normal force (763 kN) on the left side but a tensile force (-451.6 kN) on the right side of the slice. This indicates that a tension crack zone was generated at the crest of the slope. The elevation of this tension crack zone was indicated by the bottom coordinate (*Y* = 1775.55 m) of this critical slice.

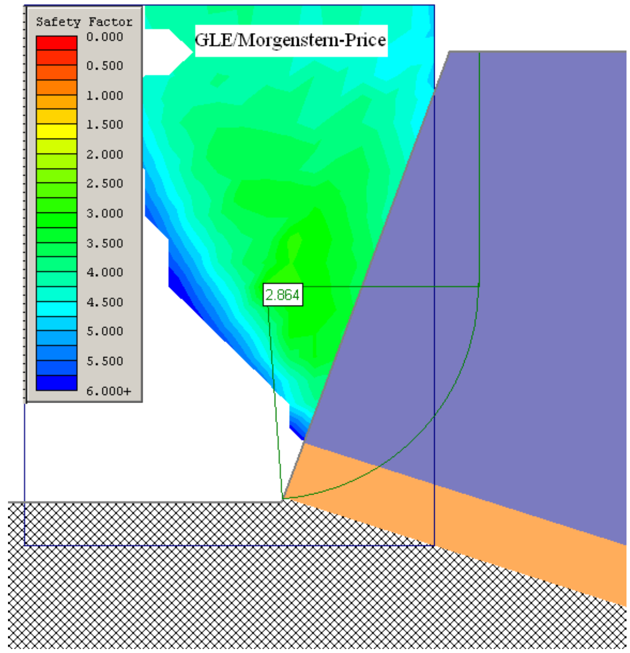

Figure 9. First calculation of factor of safety using GLE/Morgenstern-Price method without consideration of tension crack zone.

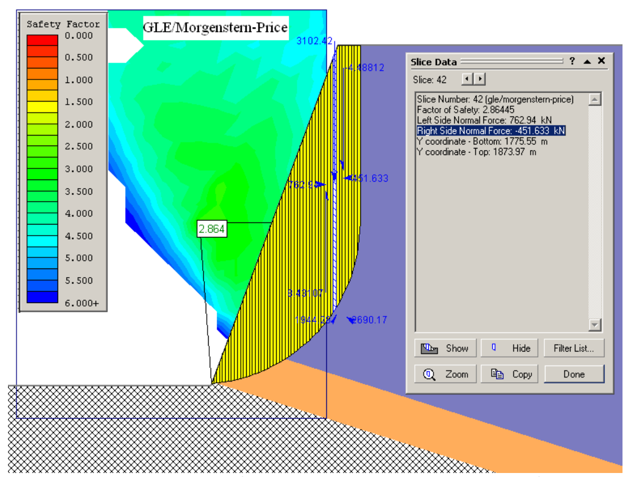

Figure 10. Interslice forces showing presence of tension zone.

Figure 11 shows the numerical model after taking into account the above identified tension crack boundary at elevation *Y* = 1775.55 m. Calculation results after introduction of the tension crack boundary is shown in Figure 12. Surprisingly, the value of the new factor of safety obtained after taking into account the tension crack zone was 3.068, which is higher than that calculated without considering the tension crack zone (Figure 9). Further examination of the interslice forces on the right side of the last slice (Slice #50) reveals that the normal force is zero as expected based on Slide manual (Figure 13).

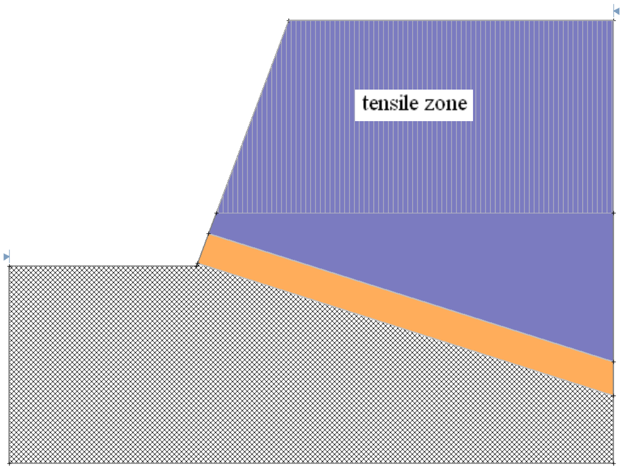

Figure 11. Introduction of tensile boundary at Y = 1775.6 m.

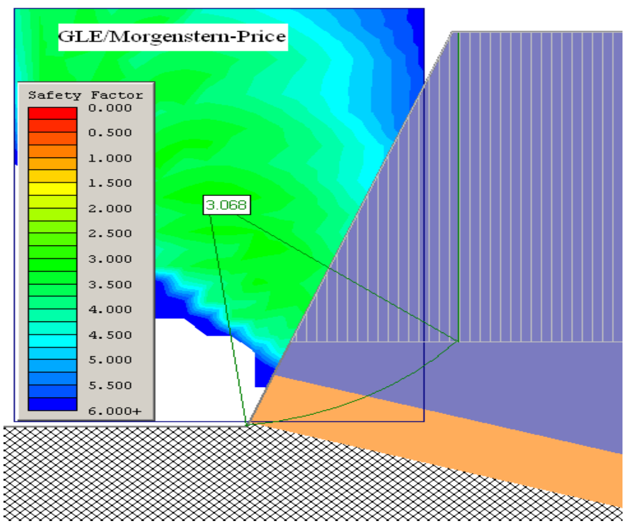

Figure 12. Factor of safety calculated after consideration of tension crack zone.

To examine this abnormal result, one first makes a comparison between Figures 7 and 13. One notes that the origin of critical failure surface in Figure 7 is much higher than the slope crest level while the origin of critical failure surface in Figure 13 is much lower than the slope crest level. In the former case, the tensile stresses react as a positive factor to the stability of the sliding block as its momentum direction is same as those of shearing forces. Thus, removal of these tensile stresses by introducing tension crack zone has effect to reduce the factor of safety. In the latter case, the tensile stresses react in a disfavored manner to the stability of the sliding block as its momentum direction is in the same momentum direction of the block weight. Accordingly, the introduction of tensile crack zone and removal of tensile stresses lead to an increase of factor of safety.

This indicates that the approach proposed in the Slide manual is not always appropriate to handle tension crack zones. By simply removing tensile stresses, the influence of the right part beyond the last slice was completely ignored. Physically, this would be similar to the case where the dam of a reservoir is built but the reservoir is empty and no water pressure is exercised on the dam (Figure 14). Obviously, this type of model that totally neglects the right part of material that was assumed to stand alone and not 'touch' the resistant part of the slope, is probably unrealistic. Project design based on such type of results is not conservative. This is particularly true in mines where production blasting could induce dynamic loading that induces interaction between the right and left parts of tension crack.

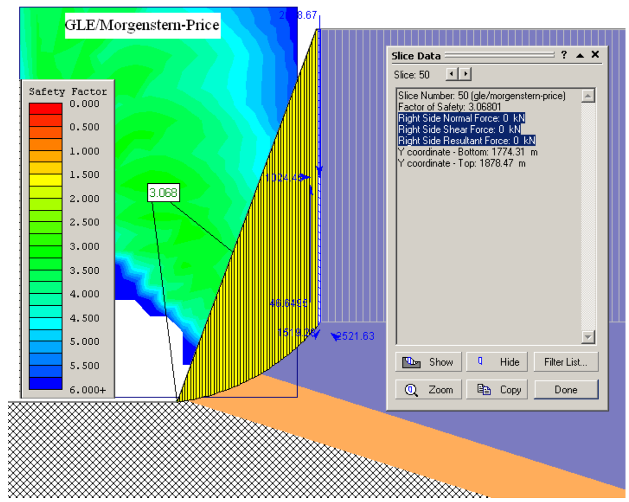

Figure 13. Zero interslice compressive normal on the side of the last slice in the tension crack zone.

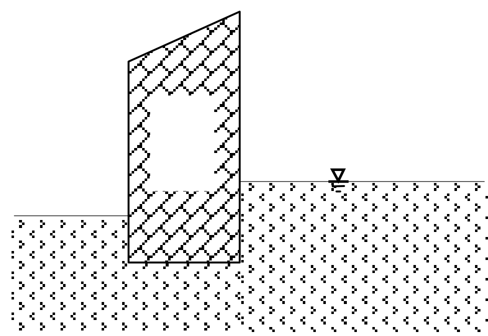

Figure 14. A conceptual gravity dam with an empty reservoir.

In order to take into account the potential negative effect of the right part beyond the tension crack, the authors proposed here to consider the residual strength of the right part of the tension crack zone beyond the last slice, as shown in Figure 15. This is a common way to consider the behavior of material after peak failure (e.g., Hoek et al. 1998; Kakou et al. 2001).

Figure 16 shows the factor of safety calculated by considering the residual strength of the material at the right side of the last slice in tension crack zone. It can be seen that the factor of safety becomes much smaller, compared to the cases where tension crack zone was neglected (Figure 9) or inappropriately considered (Figure 13).

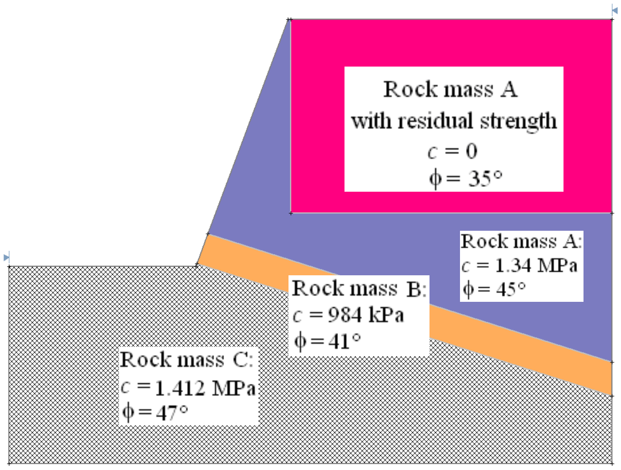

Figure 15. Introduction of residual strength to the tensile crack zone beyond the side of the last slice.

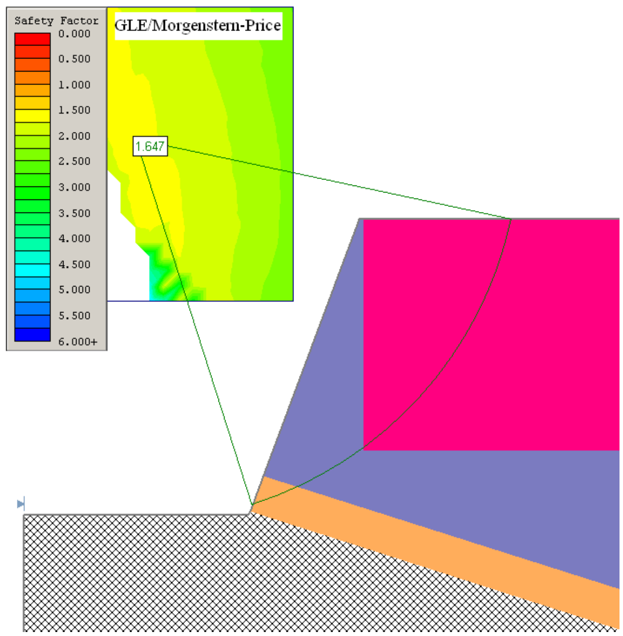

Figure 16. Recalculation of factor of safety after consideration of the residual strength.

4 DISCUSSION

4.1 Comparison with Hoek-Bray Chart

Hoek and Bray's empirical chart method is commonly used in open pit mine projects. For a given slope geometry with given material strengths, the factor of safety can be estimated by following the procedure below (Figure 17):

Step 1: to calculate the value of $c/(\gamma H\tan\phi)$ and drawing a longitudinal line of $c/(\gamma H\tan\phi)$

Step 2: to get the crossover point between the longitudinal line of $c/(\gamma H\tan\phi)$ and a pseudo latitudinal line corresponding to the slope angle α

Step 3: to draw a vertical and a horizontal line starting from the above crossover point. A value of $\tan\phi/FS$ is obtained at the crossover point between the above horizontal line and the ordinate axis. Another value of $c/(\gamma H FS)$ corresponds to the crossover point between the above vertical line and the abscissa axis.

Step 4: To calculate the factors of safety from the above two obtained values of $\tan\phi/FS$ and $c/(\gamma H FS)$.

It should be mentioned that Hoek-Bray's empirical method was established for regular and simple slope geometries. For complex irregular slope geometries, numerical tools have to be used.

For the case shown in Figure 3, the slope geometry is simple and regular. Thus, Hoek-Bray's chart method can be applied. This is shown in Figure 17. One first obtains:

$$\frac{c}{\gamma H \tan\phi} = \frac{1.34\,\text{MPa}}{0.027\,\text{MN/m}^3 \times 89\,\text{m} \times \tan 45^\circ} = 0.56$$

Considering the slope angle of 70°, one obtains:

$$\frac{c}{\gamma H\,\text{FS}} = 0.164 \text{ or FS = 3.4}$$

and

$$\frac{\tan\phi}{\text{FS}} = 0.29 \text{ or FS = 3.45}$$

These values are slightly lower than the factor of safety obtained by the numerical modeling without considering tension crack zone (Figure 5), but much higher than the numerical results after taking into account the tension crack zone (Figure 7). This indicates that Hoek-Bray's empirical chart method may overestimate the stability of slopes.

For the case shown in Figure 8, the slope was constituted of 3 inclined layers. Thus, it is not appropriate to directly apply the chart of Hoek and Bray (1981). However, lower and upper bound solutions can be obtained by considering that the slope is constituted of one material each time. This is shown in Figure 18. If the slope is assumed to be constituted of Rock mass A, one then obtains:

$$\frac{c}{\gamma H \tan\phi} = \frac{1.34\,\text{MPa}}{0.027\,\text{MN/m}^3 \times 131\,\text{m} \times \tan 45^\circ} = 0.38$$

Considering the slope angle of 69.5°, one obtains:

$$\frac{c}{\gamma H\,\text{FS}} = 0.142 \text{ or FS = 2.67}$$

and

$$\frac{\tan\phi}{\text{FS}} = 0.38 \text{ or FS = 2.63}$$

On the other hand, if one considers that the slope is constituted of Rock mass B, one obtains:

$$\frac{c}{\gamma H \tan\phi} = \frac{984\,\text{kPa}}{27\,\text{kN/m}^3 \times 131\,\text{m} \times \tan 41^\circ} = 0.32$$

Considering the slope angle of 69.5°, one obtains:

$$\frac{c}{\gamma H\,\text{FS}} = 0.132 \text{ or FS = 2.11}$$

and

$$\frac{\tan\phi}{\text{FS}} = 0.43 \text{ or FS} = 2.02$$

Above calculations using the empirical chart method indicate that the factor of safety FS should be between 2.02 and 2.67 for the geometry and material strength shown in Figure 8. However, previous numerical modeling gave a factor of safety of 1.65, which is even lower than the lower bound value obtained with the chart of Hoek and Bray. This indicates again that Hoek-Bray's empirical chart method may overestimate the slope stability and lead to a non-conservative design.

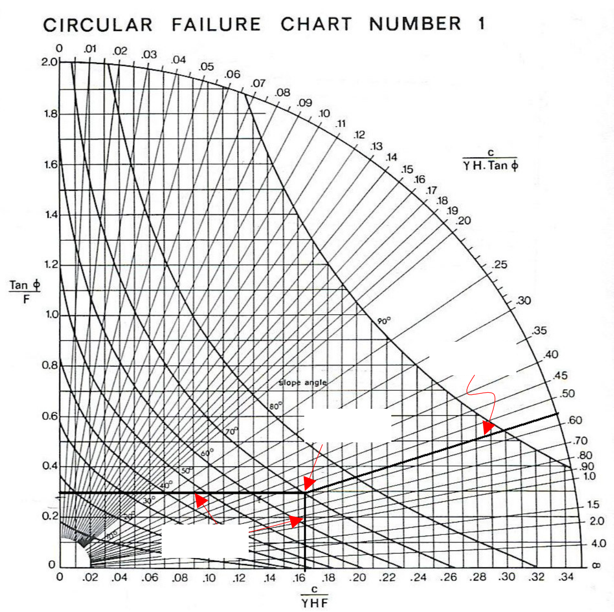

Figure 17. Estimation of the factor of safety for the geometry given in Figure 3 using Hoek-Bray's empirical chart method (Hoek and Bray 1981).

4.2 Numerical modeling with Slide

Above numerical modeling results using Slide highlight several points. First, it was noted that the identified tension crack zones are very large compared to the slope geometry (see Figures 6 and 11). These tension crack zones are identified by examining the interslice normal forces. The bottom coordinate of the slice on which is exercised a compressive normal force on one side and a tensile normal force on the other is considered corresponding to the depth of the tension crack zones. As the horizontal (and vertical) normal stresses increase with depth, the stress regime may change from tension to compression if one considers the position from the top to the bottom of the vertical slice. Thus, the depth of the tension crack zones could be overestimated by the approach proposed in the Slide manual. Nonetheless, this overestimation of the tension crack zone tends to underestimate the factor of safety and leads to a more conservative design.

Also, it is noted that the critical failure surfaces may significantly change when identified tension crack zones are introduced in the new models (Figure 5 versus Figure 7 and, Figure 9 versus Figures 13 and 16). This is due to the fact that an introduction of tension crack zones means a significant change in physical model.

Finally, it should be indicated that the approach proposed by the authors for the case shown in Figures 15 and 16 is not the unique method to obtain a more conservative design. Other alternative methods, for instance, considering the left or the whole part of the tension crack zone as residual strength material, can also be envisaged.

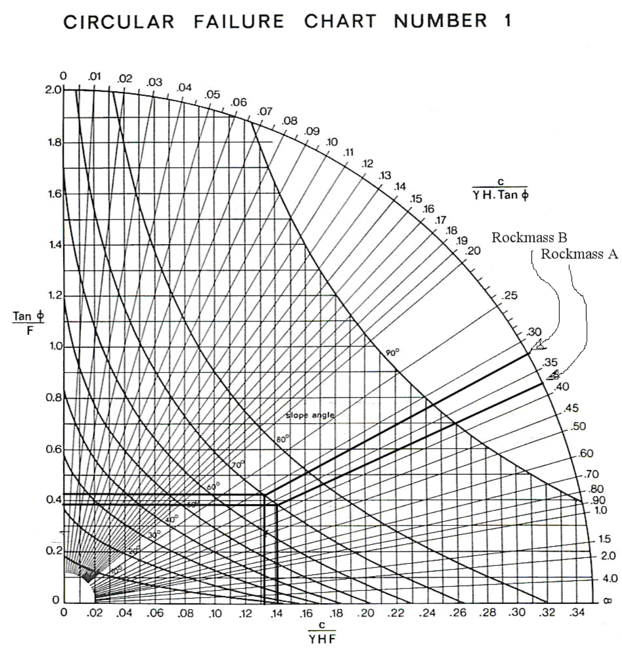

Figure 18. Calculation of lower and upper bound values using the chart of Hoek and Bray (1981).

5 CONCLUSION

The formation of cracks at the top of a slope is an obvious sign of instability. It is important to take into account the tension crack zone with numerical modeling. In this paper, the authors have shown that the tension crack zone, if neglected or inappropriately considered, can lead to erroneous results and non conservative design. To overcome the limitation included in Slide, the authors proposed a new approach by assuming the tension crack zone beyond the last slice behaving as residual strength material. The results showed that this approach leads to more conservative design. Further comparison between the commonly used Hoek-Bray's empirical chart method and numerical modeling by taking into account the tensile crack zone indicates that the former method has tendency to overestimate the slope stability and may lead to a non-conservative design.

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