New slope stability considerations for deep open pit mines

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Synopsis

There has been disappointingly little development in the analysis of rock slopes in open pit mines over the past 30 years. A brief review of literature shows that the application of numerical stress analysis methods to open pit mine slope stability has become only relatively common in recent times, and that there are as yet no standardized approaches. The lack of development in general, and of robust, standardized approaches in particular, is surprising in view of the ‘ultra’ deep open pit mines that are being developed to depths in excess of 1000 m.

In this paper, the results of a substantial programme of two dimensional and axisymmetric analyses of open pit slopes are described. Variations in the following parameters were taken into account in this programme: slope angle, slope height and horizontal to vertical in situ stress ratio. The evaluation of the data has concentrated on the tensile stresses and the extension strains in the slopes. This is believed to be the first publication dealing with strain distributions in slopes. The occurrence of zones of tensile stress was very limited. These zones occur in the crests of slopes, except in the case of low horizontal to vertical stress ratios, in which case the tensile zone is in the floor of the pit. In contrast, very large zones of extension strain can occur, and this finding represents a significant new aspect in slope stability that has not been considered before. The greatest magnitudes of extension strain occur near the toe of the slope, either in the slope itself, or in the floor of the pit. The magnitudes of the strains are considered to be large enough to result in fracturing of intact rock, and the fracture orientations predicted are adverse for slope stability. The large zone in which such extension failure could potentially occur in a 1200 m deep pit is typically more than 100 m horizontally behind the toe and about 400 m up the face from the toe.

Fracturing that is extension in nature is common in competent, brittle rocks and often develops with some violence and little or no warning. Such ‘strain bursting’ produces easily measurable seismicity, events often being audible as well. In the slope situation, the expected physical manifestation of this behaviour would be popping off of rock slabs and plates of rock from slope surfaces and popping up of the pit floor, as well as the formation of new fractures within the rock mass. Such behaviour may cause overall slope failure, or may initiate failure, which may then be driven to overall slope failure by other influencing factors or combinations of factors.

In addition to instability resulting from the fracture surfaces themselves, all induced fracture surfaces could interact with natural geological structures to facilitate formation of a significant failure surface. With suitably orientated joints, extension strains are likely to manifest themselves in the opening up of such joints and hence in the loosening of the rock mass in a preferential orientation, with potential effects on groundwater flow patterns.

Introduction

In the 1960s and 1970s considerable research was carried out into the stability of rock slopes in open pit mines. It was also during this period that early development of numerical analysis methods took place, but there was relatively little application of them to the evaluation of slope stability. Most of the work carried out concentrated on the use of limit equilibrium techniques, and the work of Hoek and Bray (1981) summarizes the state of the art at that time. As indicated by Stacey (1996), there has been surprisingly little development in the technology of stability evaluation of open pit mine slopes in the 30 years since this period, and limit equilibrium techniques are still most commonly used.

The lack of development in slope stability evaluation is also surprising since, as pointed out by Stacey (1993), many of the pits designed in the 1960s and 1970s were reaching their full depths after about 20 to 30 years. Figure 1 shows a plot of a historical record of pit depths and corresponding slope angles for past and present pit operations. This illustrates the limited experience that exists for very deep pits. In the past 10 years, open pit planning has ventured into the ‘ultra-deep’ pit scenario, with pits in excess of 1000 m being planned. This depth is significant, even for underground mining, and stress levels are correspondingly significant, in particular if the horizontal in situ stresses exceed the vertical stresses. At such depths, the rock is likely to be competent and unweathered except for fault zones, and the stress levels around the pit could lead to induced failure of the rock. It is

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Figure 1—Case study data on overall pit slope angle versus slope height (modified after Sjoberg, 2000)

therefore appropriate that new attention should be paid to the effects of stresses on the stability of the slopes of these mines.

In this paper, a brief review of the application of stress and numerical analysis techniques to slope stability is presented. Then a programme of stress analyses of two-dimensional and axisymmetric open pit slopes is described, and the results of these analyses are summarized. A range of pit depths from 400 m to 1200 m, and a range of slope angles from 30° to 75°, have been considered in this programme. Several in situ horizontal to vertical stress ratios have also been considered, as well as the effects of different values of Poisson’s ratio.

Review of the application of stress analyses in the evaluation of slope stability

After the development of the finite element method of stress analysis in the 1960s, there were early applications of the method to slopes (for example Duncan and Goodman, 1968; Gates, 1968; Mahtab and Goodman, 1970). Extensive investigations into the elastic stress distributions in two-and-three dimensional slopes were carried out by Stacey (1970, 1972, 1973). Factors taken into account in these investigations were the angle of inclination of the slopes, the floor width of the open pit, the horizontal in situ stress field, and the value of Poisson’s ratio. A set of charts, presenting dimensionless contours of stresses in slopes for various slope angles, was prepared to allow a quick indication of stress at any point in a slope to be determined (Stacey, 1970). It was also found that:

- opposite slopes of an open pit do not interact when the floor width of the pit exceeds about 0.8 times the slope height
- a large horizontal in situ stress field has a major influence on the stress distributions in slopes
- the horizontal stress field overrides the effect of any variation in Poisson’s ratio.

The aim of the three-dimensional investigation carried out (Stacey, 1973) was to study the influence on the stress distribution of the following variables: the plan configuration of the slope; the horizontal in situ stress field; and, unequal horizontal stress fields in orthogonal directions. Some of the results serve to emphasize important considerations in the design of open pits. With regard to this paper, dealing with two-dimensional and axisymmetric slopes, the following conclusions are relevant:

- stresses at the toe of the slope (an area of stress concentration) were found to be compressive in both radial and circumferential directions
- compressive circumferential stresses will constrain and tend to stabilize slopes. Where circumferential stresses are tensile there will be no constraint and it will be possible for the slope to ‘bulge’. The results indicated that observable bulging of the slope is only likely to begin at 5% to 10% of the slope height above the toe.

Some application, or development, of stress analysis methods to rock slopes has taken place from time to time. Kalkani (1976) described the application of finite element analyses to the evaluation of the stability of reservoir slopes. Actual stability was not quantified, but calculated zones of tensile minor principal stress corresponded with zones of observed cracking and rock movement. Kalkani and Piteau (1976) used the same approach to evaluate toppling failure. The calculated tensile zone approximated reasonably well the extent of the slope that had previously undergone tensional failure during periods of high rainfall. Lee (1978) also found correspondence between the theoretical tensile zone, calculated by finite element analysis, and the observed extent of vertical jointing at the Niagara Falls.

More sophisticated non-linear finite element analyses, incorporating joint elements, were applied by Valliappan and Evans (1980) and Brown et al. (1980). In both cases there was qualitative agreement between the calculated results, mainly the location of tensile stresses, and the observations of instability.

Hocking (1978) dealt with the potential of the distinct element method, but did not apply it to a real slope problem. Dowding and Gilbert (1988) did the same for analysis under seismic and blast vibration loading, but also did not consider a real slope. A real problem was considered by Ishida et al. (1987), who used a simple distinct element model of a toppling rock slope. Their analysis yielded similar results to the toppling behaviour observed, and provided information on the geological processes involved in the toppling.

In the application by Mitsui and San (1988), a non-linear finite element analysis was used to trace the development of a failure surface within the slope, and a conventional factor of safety approach on this surface was used to quantify the stability. The beneficial effect of reinforcement was then...
analysed using bar elements for the reinforcing, with elasto-plastic interface elements between the bar and the soil. Although this analysis was for a soil slope, the same approach could be used for a rock slope without major planes of weakness. The approach of Chalaturnyk et al. (1989), also for a soil slope, can be considered to be the same in concept.

With regard to the analysis of slopes in a 'homogeneous' rock mass, the use of rock mass classification methods has become common for the determination of rock mass strength and deformation parameters. The rock mass classification numbers Q (Barton et al., 1974) and RMR (Bieniawski, 1989) and, more recently, the Geological Strength Index GSI (Hoek and Karzulovic, 2000), have been correlated with the rock mass modulus, rock mass strength parameters (both Hoek-Brown and Mohr-Coulomb) and the 'unconfined compressive strength' of the rock mass. Correlations of significance are with the rock mass deformation modulus (Serafim and Pereira, 1983) and with the rock mass strength parameters. The latter have recently been encapsulated in a computer package RocLab (Rocscience, 2002), allowing very simple determination of Hoek-Brown parameters and cohesion and friction values. This package also provides for the determination of the rock mass modulus, using an 'average' correlation from empirical correlation results, and a rock mass uniaxial compressive strength. Laubscher (1993) describes a different approach for the determination of rock mass strength and, more recently, Barton (2000) has provided an equation linking Q with rock mass strength.

Singh and Dhar (1994) and Singh et al. (1995) based their rock mass input parameters on rock mass classification data, and made use of a finite difference method to evaluate the stability of rock slopes in open pit mines. In the first paper, the indication of failure was the 'plasticity indicator' contained within the program, and in the second it was the localized factor of safety against Mohr-Coulomb shear failure. In both cases limit equilibrium analyses were also carried out, and provided similar indications of stability. Du Plessis and Martin (1991) used the same method. However, they determined the appropriate cohesion and angle of friction for the rock mass by calibrating the model against slope monitoring data, and then used the model to assess the stability of the final pit. It is considered that this is a much better engineering approach than the absolute approach adopted in the two more recent papers, and highlights the problem of prediction as opposed to the problem of design.

Prediction of behaviour, which is very significantly involved in the analysis and design of open pit mine slopes, requires a very thorough understanding of the mechanisms of deformation and behaviour of the slopes. In design it is possible to achieve a satisfactory result by extrapolation of existing behaviour (without knowing the actual mechanisms involved). However, satisfactory absolute prediction of behaviour is unlikely to be successful if the following are not used: the correct mechanisms, or combinations of different mechanisms, of behaviour; the correct strength parameters; the correct deformation parameters; and the correct failure criteria. As indicated by Stacey (2000), the use of a rock mass classification approach, which is commonly used to estimate such parameters, is unlikely to be satisfactory for absolute prediction since all correlations are based on empirical data. Such correlations are 'smear' correlations and cannot hope to provide data for successful absolute prediction. If successful predictions are obtained, they are likely to be by luck rather than by confident engineering.

The likely errors in absolute prediction are well illustrated by the exercise in the calculation of subsidence described by Kay et al. (1991). Nevertheless, there is still very good value to be had from the use of such approaches in sensitivity analyses.

The calibration approach was used by Board et al. (1996), Hencher et al. (1996) and Coggan and Pine (1996). In these three papers, real slopes are dealt with, and use is made of measured deformations to calibrate models prior to their use for prediction of slope behaviour into the future. Whereas a discontinuum approach only was used in two of the papers, Board et al. (1996) made use of both continuum and discontinuum numerical analyses. They found that the continuum approach could model the discontinuous rock mass successfully, and it was the preferred approach for computational reasons. The steps involved in the approach were:

- development of a conceptual model of the slope, taking into account the geological structure and structural regions, the observed deformation behaviour, the measured deformations, failures that have occurred, etc.
- determination of the appropriate constitutive model of rock mass behaviour
- determination of rock mass properties using rock mass classification; calibration of models—confirmation of the boundary and initial conditions, sensitivity studies to establish appropriate material properties, comparison of model results with observations and measurements, and modifications if necessary
- application of the 'final' model to determine behaviour as a result of future mining.

In terms of the common application of numerical methods in the evaluation of the stability of rock slopes, it appears that this has only recently occurred. Review, state-of-the-art papers, and chapters on slope stability that appear in texts, of about 10 years ago (Chen, 1995; McCreath, 1993; Richards, 1992; Richards and Atherton, 1987), make no mention of such approaches in rock slope stability. However, from a recent specialized publication (Hustrulid et al., 2000), it is apparent that the use of such methods in the mining industry is now quite common (Valdivia and Lorig, 2000; Stewart et al., 2000; Sjoberg et al., 2000; Sjoberg and Norstrom, 2000; Rose and Sharon, 2000; Jakubec et al., 2000; Pierce et al., 2000). Lorig (1999) and Zettler et al. (1999) investigated numerically the effect of three dimensions on slope stability. In spite of the now common use of numerical approaches, numerous questions remain, not the least of which is that of absolute prediction of instability.

It is considered that the paper by Board et al. (1996) probably represents a state-of-the-art development in the application of stress analysis techniques to the evaluation of slope stability. Apart from this paper, little 'quality' progress appears to have been made in the application of stress analysis approaches to rock slope stability since the 1970s. This can be viewed as a criticism of lack of development by rock slope researchers and practitioners, or an indication that...
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Developments have been made preferentially in other areas. The latter is probably the case since development has taken place in limit equilibrium approaches and in the application of probability and reliability theory to slopes. In a recent state-of-the-art review, Hoek et al. (2000) concluded, ‘In the current state of practice, heavy reliance is placed on limit-equilibrium analyses, which are often too simplistic, particularly for larger slopes. Numerical modeling is finding increasing application, particularly for defining potential failure modes. However, some degree of calibration is required before the numerical models can be considered predictive in the design sense. This also is an area requiring considerable future investigation.’

Although it is clear from the above that attention is currently being directed at the occurrence of stresses in slopes, and the consequent stress-related behaviour of the rock mass, it is not apparent that any consideration has been given to the distribution of strains in slopes and the effects that such strains could have.

From the above brief review of literature, the following may be concluded:

- the limited progress made with the application of numerical analysis techniques to rock slope stability over the past 30 years is very disappointing, and the use of stress analysis approaches for prediction of slope stability in open pit mining does not appear to be well established
- there is an insufficient number of cases of excavated (open pit) slopes with slope heights in excess of about 500 m to constitute a satisfactory experimental database for ultra deep open pits
- where stress analysis approaches have been applied, the input parameters for the analyses have usually been derived from rock mass classification based empirical correlations and assumed rock mass failure criteria. Such approaches are likely to introduce very significant variability into the analyses, and the assumption, in the stress analysis program, of a particular failure criterion dictates failure behaviour in the model. As a consequence, the results will probably be unsatisfactory for absolute prediction of stability
- success appears to have been achieved, even using very early numerical analysis techniques, in the qualitative correlation of theoretically predicted zones of tension with observed zones of instability and failure
- the use of stress analysis approaches to slope stability have concentrated on stress and failure aspects, and there appears to have been no attention given to strain distributions in slopes.

Recent stress analysis modelling of two-dimensional and axisymmetric open pit mine slopes

To address some of the issues raised above, a substantial programme of two-dimensional and axisymmetric stress analyses of various slope geometries has been carried out using finite element analysis. Only elastic analyses were carried out, and fine meshes were used to ensure, particularly, that accurate results were obtained in the proximity of the excavation boundaries. The following parameters were taken into account:

- Pit depths: pit depths of 400 m, 800 m and 1200 m were considered. Pit geometries, at an intermediate stage of mining, were modelled to determine their influence on the stress and strain distributions. The pit geometries and the excavation steps are illustrated in Figure 2 for one of the slope angles modelled.
- Pit slope angles: slope angles of 30°, 40°, 45°, 50°, 55°, 60°, 70° and 75° were analysed in most cases.
- Horizontal to vertical in situ stress ratios (k ratios): values of 0.5, 1.0, 2.0, 3.0 and 4.0 were used in most cases.
- Out-of-plane stress (for two-dimensional analyses): the results presented in this paper are derived from the assumption of plane strain conditions.
- Poisson’s ratio: the width of the base of the pit exceeded 0.8 times the height of the slope in all cases, and therefore, based on the results of previous analyses (Stacey, 1970), variations in Poisson’s ratio have little effect on the stress results. A value of 0.17 for Poisson’s ratio, being representative of strong brittle rock, was used for all analyses presented in this paper.
- Modulus of elasticity: in all cases the modulus of elasticity used was 80 GPa. For elastic analyses, the stress results are independent of the modulus of elasticity used, but the strain results are directly proportional to the value of the modulus.

The results of the analyses will be presented in the following sections. The tensile stress results will be dealt with first, but the evaluation will subsequently concentrate on a new consideration in slope stability—the occurrence and distribution of extension strains in slopes around deep open pits.

Tensile stress distributions around open pit mine slopes

The two-dimensional and axisymmetric analysis results will be dealt with separately in the following sections.

Tensile stress results from two dimensional analyses

The locations of tensile stress zones are as follows:

- for a k ratio of 0.5, the tensile stress zone is beneath the floor of the pit
- for k ratios greater than 1.0, the tensile stress zone is in the crest of the slope
- only very localized tensile stresses occur, but no significant tensile zones are found to be present at the toe of the slope.

Figures 3 and 4 illustrate tensile stress distributions around 30° and 60° slopes, 1200 m high.

For k ratios of 1.0 and greater, both the extent of the tensile zone in the crest and the tensile stress magnitude increase with an increase in k, and also increase with increase in slope angle. These results are partly in agreement with and partly contradictory to the location and extent of tensile zones described by Stacey (1970). In the recent analyses no significant tensile zones were found to be present at the toe of the slope or up the surface of the slope, except as part of the crest zone. The discrepancy between these results and those of the earlier work is probably due to
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The limited capabilities and accuracy of the finite element analyses carried out in the earlier work.

The variations of the maximum value of tensile stress with \textit{in situ} stress $k$ ratio and with slope angle are shown in Figures 5 and 6 for a 1 200 m slope height. Similar behaviour occurred for other slope heights. It can be seen that, for the higher values of horizontal to vertical \textit{in situ} stress ratios, the tensile stresses induced behind the crest of the slope can be significant. It is therefore not surprising that tension cracks may develop behind the slope crest.
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**Tensile stress results from axisymmetric analyses**

The extents of tensile stress zones and the magnitudes of tensile stresses are reduced for an axisymmetric pit. For a k ratio of 0.5, zones of tensile stress do not occur. For k ratios of 1.0 and greater, a tensile zone occurs at the crest of the pit. The extent of this zone and the stress magnitudes within it increase with increases in k ratio and slope angle. The zone encroaches increasingly down the face of the slope with higher values of k. Tensile stress distributions for a 60° slope of an axisymmetric open pit, 1 200 m deep, are illustrated in Figure 7 for a k ratio of 2.0. No significant tensile stresses occur for a 30° slope with this k ratio.

The variations of tensile stress magnitude in the crest of the slope with *in situ* stress and with slope angle are shown in Figures 8 and 9. These distributions are significantly different from those in the two-dimensional slopes shown in Figures 5 and 6.

**Extension strain distributions around open pit mine slopes**

Although stresses in slopes have been considered over the years, from the brief literature review carried out, it does not appear that any consideration has previously been given to the occurrence of strains in slopes. The work reported in this section, dealing in particular with extension strains, therefore
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represents a new development in the consideration of open pit mine slope stability.

The extension strain is defined as the minimum principal strain $\varepsilon_3$ (in a compression positive convention) and is calculated from the principal stresses using the three-dimensional elastic equation:

$$
\varepsilon_3 = \left[ \frac{\sigma_3 - \nu(\sigma_1 + \sigma_2)}{E} \right]
$$

where $\sigma_1$, $\sigma_2$, $\sigma_3$ are the three principal stresses

$\nu$ is Poisson’s ratio

$E$ is the modulus of elasticity

$\varepsilon_3$ depends on all three principal stresses and can be extension in nature, even in a triaxially compressive stress field. It is clear therefore that it will depend on the magnitude of the out-of-plane stress used in the two-dimensional stress analysis. The results for the two-dimensional analyses presented in this paper have all assumed that the out-of-plane stress corresponds with a plane strain condition. The occurrence of a zone of extension strain around an open pit implies that the rock mass has ‘expanded’ in at least one direction in that zone.

It is clear from the above equation that the smaller the value of $E$, and the larger the value of Poisson’s ratio, the greater will be the magnitude of extension strain.

As for the tensile stress results presented in the section above, the extension strains around two-dimensional and axisymmetric open pits will be dealt with separately.
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Figure 7—Tensile stress distributions for axisymmetric 60° open pit slope, k = 2.0

Figure 8—Variation of the magnitude of the induced maximum tensile stress with k ratio—axisymmetric slopes

Figure 9—Variation of the magnitude of the induced maximum tensile stress with pit slope angle—axisymmetric slopes
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**Extension strains around two-dimensional slopes**

The results presented above demonstrate that the occurrence of zones of tensile stress around open pit slopes is relatively limited. In contrast with this, the analyses show that substantial zones of extension strain occur around the open pit for all in situ stress conditions and for all slope angles.

Figures 10 and 11 illustrate the extents of the extension strain zones for two-dimensional slopes with angles of 30° and 60°, and a height of 1 200 m.

From these Figures it can be seen that the maximum magnitudes of extension strain occur at the toe of the slope, either in the slope or in the floor of the pit. The magnitudes are greater for higher values of \( k \). The zones of extension strain are larger around the bowl of the pit for flatter slope angles and higher \( k \) ratios. Significant zones of extension occur in the crest of the slope only for higher \( k \) ratios—there is no significant zone of extension strain for \( k \) values of 0.5 and 1.0.

The extents of the zones shown in Figures 10 and 11 are very substantial, and have been quantified by their horizontal and vertical extents. The horizontal extent is represented by the horizontal distance between the toe of the slope and the boundary of the zone. The vertical extent is represented by the vertical distance between the floor of the pit and the boundary of the zone, measured along the vertical axis of symmetry. The results are shown in Figures 12 and

![Figure 10—Extension strain distributions for two dimensional slopes, \( k = 0.5 \)](image-url)
13, illustrating the effects of both the k ratio and the slope angle. In fact the extents of the zones in these figures are measured to where the extension strain exceeds a value of 0.00001, since this is better defined than the point of zero extension strain. The actual zones of extension are therefore slightly greater than indicated. It can be seen from Figures 12 and 13 that the zones of extension can be very large, of the order of many hundreds of metres behind the slope face and beneath the pit floor, depending mainly on the k ratio and the pit slope geometry.

It is evident that both the magnitude of the extension strain and the size of the zones of extension strain are significantly dependent on the value of the k ratio. In the analyses carried out, the k ratio was assumed to be constant with increase in depth. The implication of this is that the horizontal stress will become very large at great depth. This is probably unrealistic, and a k ratio that could be high near the surface, will in practice probably reduce at great depth to a value in the region of 0.5. This in situ stress profile will probably be different in different locations in the world. A check was carried out to determine the effect of a reducing k ratio with depth, and the result is a decrease in both magnitude and extent of the extension strains. However, the conclusions drawn from the research work remain valid. The in situ stress profile effect is an area that requires further study.

Figure 14 illustrates the distribution of extension strain in a pit at an intermediate stage of excavation, demonstrating how the extent of the zone and the localization of strain concentration can change during mining.

**Extension strains around axisymmetric slopes**

For the axisymmetric analyses, the results corresponding with Figures 10 and 11 for the plane slopes are shown in Figures 15 and 16. It can be seen that the strains are not as concentrated at the toe as in the two-dimensional cases. The extents of the zones are slightly smaller than those for the plane slopes, but are still very substantial.

The quantified extents of the extension zones, illustrating the effects of k ratio and slope angle, are given in Figures 17 and 18.

**Discussion of the results of the modelling**

The discussion in this section will consider tensile stresses briefly, but the focus will be on the extension strain results obtained from the finite element analyses. These results have shown that very large extension strain zones will develop around the slopes and floors of open pits. It is to be noted that the geometry of the pit in plan (such as the occurrence of convex slopes, resulting in ‘noses’ in the pit) will have a significant influence on the occurrence of tensile stresses and extension strains. These effects will be considered in future research. Some of the questions that may arise from the findings of the present analyses are:

➤ what is the significance of the occurrence of tensile stress?
➤ what is the significance of the occurrence of extension strain?
➤ will the stability of the slopes be affected adversely?
➤ will there be interaction with the geological structure in the slope?
➤ will there be failure of the rock material and rock mass?
➤ will there be any influence on groundwater conditions?

These issues will be considered in the discussion in the following sections.
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**Occurrence of tensile stresses**

The results have shown that, perhaps, the only significant tensile stress zone is that which occurs in the crest of the slope. This corresponds in practice with the occurrence of tension cracks that are commonly observed behind the crest of a failing slope. A tensile stress zone only occurs in the floor of the pit for low horizontal to vertical \textit{in situ} stress ratios.

Perhaps the most significant aspect is that, wherever tensile stress occurs, extension strains also occur. It is therefore considered that the occurrence of the latter is of more significance.

**Magnitudes of the extension strains**

As indicated above, the magnitude of the extension strain calculated is directly proportional to the modulus of elasticity used in the analysis. The results presented above are for a modulus of elasticity of 80 GPa. If the modulus of elasticity were 40 GPa instead of 80 GPa, for example, these strains would double. Note, however, that the extents of the zones of extension are not influenced by the modulus.

As the height of the slope increases, and as the \( k \) ratio increases, the stress levels will increase and, correspondingly, the magnitudes of the extension strains will also increase. For a 400 m deep pit, the maximum extension strain...
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Figure 14—Extension strain distributions for a two-dimensional 60° slope at an intermediate mining stage, $k = 2.0$

Figure 15—Extension strain distributions for axisymmetric slopes, $k = 0.5$
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Figure 16—Extension strain distributions for axisymmetric slopes, k = 2.0

Figure 17—Horizontal extents of extension strain zones for axisymmetric slopes

Open Pit Depth

Horizontal extent of extension strain zone

Slope angle (degrees)
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Magnitudes calculated vary from about 0.00001 for k of 0.5 to about 0.0001 for a k of 2.0. For a 1 200 m deep pit the corresponding strain values are about 0.0001 and about 0.0003. These magnitudes of strain are considered to be large enough to cause fracturing to develop in intact rock material. In terms of the extension strain criterion for fracture of brittle rock (Stacey, 1981), critical extension strain levels at which fracturing can occur are in the 0.0001 to 0.0003 range. The stress conditions are therefore conducive to the development of extension fracturing around and adjacent to the toes of slopes (in the pit floor and in the slope face area). From the analyses carried out, these conditions could apply for 400 m high slopes when the k ratio is about 2 or greater. They would apply for 1 200 m high slopes under any k ratio. It can therefore be concluded that failure of the rock material and rock mass will occur, and that this might have a significant negative effect on the stability of the slope.

**Orientations of potential fracture surfaces**

The orientations of extension fractures will be normal to the minimum principal stress. In the proximity of excavation surfaces, the direction of the minimum principal stress is...
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normal to the surface and hence extension fractures will be sub-parallel to the excavation surface. As an example,

Figure 19 illustrates the principal stress trajectories around a 60° slope, 1 200 m high (k of 2.0), as well as in the region of an earlier 'toe' at an intermediate stage of mining. It is therefore likely that fracture surfaces will develop behind the pit face above the toe of the slope and in the pit floor, parallel to the floor. In the toe region, the principal stresses 'curve' around the toe and the fracture orientations will correspondingly follow these orientations.

In Figure 20, an expanded interpretation is given of the probable orientations of fractures in the toe and slope face regions. This shows that inclined fractures are likely to develop in any toe region and that slope face parallel fractures are likely to develop behind the face, away from the toe. These orientations are likely to be adverse for stability of the slope—the inclined surfaces will facilitate sliding out from the face and the face parallel surfaces will promote the formation of 'columns' or plates. These could be involved in slope failure, owing to sliding out or buckling out.

From the analyses carried out, the extent of the zone of potential fracturing is very substantial. For example, for an 800 m high, axisymmetric 60° slope (k ratio of 2.0), fracturing could occur to a horizontal depth of about 50 m into the rock mass behind the toe region and over a height of between 50 m and 100 m up the slope face. In comparison, for a 1 200 m pit, fracturing could occur to a horizontal depth of more than 100 m behind the toe of the slope, and over a height of about 400 m up the slope face. Similar extents apply, for example, for a 45° slope, 1 200 m high. This illustrates the influence of the depth of the open pit. The implication from this is that adversely orientated fracture planes can develop in the tightly confined rock mass beyond the surficial zone of blast damage, and the potential for fracturing damage is unlikely to be inhibited by the loosening effects of blasting. The further implications are that there may be limits to the depths to which open pit operations can progress without the occurrence of stress-induced instability.

It is likely that, at greater mining depths, rocks will be more competent and less weathered. Fracturing that is extension in nature is more common in more competent, brittle rocks and often develops with some violence and little or no warning. The mechanism involved would be a form of 'strain bursting' which produces easily measurable seismicity, events often being audible as well. In the slope situation, the expected physical manifestation of this behaviour would be popping off of rock slabs and plates of rock from slope surfaces and popping up of the pit floor, as well as the formation of new fractures within the rock mass.

There is likely to be some time dependency in the development of fractures. Since the size of the open pit increases slowly, there is an abundance of time for the stresses around the pit to readjust and to interact with the rock material and rock mass, promoting the development of fractures. Such behaviour may cause overall slope failure, or may initiate failure, which may then be driven to overall slope failure by other influencing factors or combinations of factors.

In addition to instability resulting from the fracture surfaces themselves, all induced fracture surfaces could interact with natural geological structures (joints, bedding planes, faults, etc.) to facilitate formation of a significant failure surface and to reduce the stability of the slope. With such adversely orientated extensions, extension strains are likely to manifest themselves in the opening up of such natural structures and hence in the loosening of the rock mass in a preferential orientation.

**Influence on groundwater conditions**

The presence of zones of extension will lead to expansion of the rock mass in a preferred direction. This, the formation of new extension fracture surfaces, the opening up of adversely orientated natural structures, and the interaction of these effects with other natural geological structures, will express itself as a zone of relaxation, in a preferential direction, around the pit. This is likely to have a significant influence on the permeability of the rock mass. This may facilitate the entry of groundwater into the rock mass, may allow channelling of water flow in particular directions, and may inhibit flow in other directions. Since groundwater pressures are a very important contributor to the instability of slopes, some of these effects may be detrimental to stability of the slopes.

**Conclusions**

From the programme of stress analyses, the results of which have been described in this paper, the following conclusions can be drawn:

- relatively limited tensile stress zones occur behind the crest of slopes for *in situ* stress conditions with k ratios greater than 1.0, and in the floor of the pit for low k values
- in contrast with the limited occurrence of tensile stresses in open pit mine slopes, very large zones of extension strain can develop around the slopes. The occurrence of extension strains in open pit slopes represents a new, and potentially very important, consideration with regard to slope stability
- the magnitudes of the extension strains increase with the depth of the pit and with the horizontal to vertical *in situ* stress ratio
- for the magnitudes of the extension strains calculated, it is likely that extension fractures will develop in the rock. As an example, for a 1 200 m deep open pit, the zone of potential fracturing could extend more than 100 m horizontally into the slope and 400 m up the face of the slope (k ratio of 2.0). Since the magnitudes of the extension strains are inversely proportional to the modulus of elasticity and directly proportional to Poisson's ratio, this potential fracture zone could be much larger for smaller moduli of elasticity and for higher Poisson's ratios
- the probable orientations of fracture surfaces, adversely inclined out of the slope near the toe and parallel to the slope face away from the toe, are such that they could have a significantly negative influence on the stability of slopes. The geometry of the fracturing could lead to the formation of slabs parallel to the slope face. These slabs could fail violently in a buckling mode. The fracture surfaces will probably also provide surfaces that can interact with, or combine with, natural geological structures to form potential failure surfaces within the slope. It is therefore possible
New slope stability considerations for deep open pit mines

that there could be a limit to the depth to which open
pits could be practically developed

► the zones of extension in the slopes represent possible
locations of changed rock mass permeability and
preferential groundwater flow.

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NOSCAR awards reinforce industry commitment
to risk management*

Welcoming industry champions, André van der Bergh,
president of the NOSA board of directors, opened the annual
NOSCAR awards at a prestigious ceremony in Johannesburg
on Friday 9 May 2003 evening.

Recognition was given to companies for the effort that
went into the achievement of a higher standard and the
adoption of internationally recognized best practices in
occupational safety, health and environmental risk
management.

For the past 30 years, the NOSCAR award has been
perceived as the ultimate achievement in occupational risk
management. The NOSCAR awards have their origin in a
‘super league’ of regional and national top achievers among
NOSA clients. Inspired by the Hollywood Oscars, the
NOSCAR acronym stands for National Occupational Safety
Credited Awards.

Unlike the traditional ‘green’ NOSCAR awards for the
NOSA Five Star System (incorporating occupational health
and safety), Friday night saw the first ‘platinum’ NOSCARs
being awarded. This shows the achievement of those
organizations that were brave enough to take up the
challenge of implementing the NOSA Integrated Five Star
System (incorporating occupational health, safety and
environmental risk management).

Van der Bergh stressed that the management and staff
of these organizations and companies had the courage to
challenge the unknown and in the process defined a new
benchmark for others to follow.

‘The need for leadership was never so great. A new
chronic crisis of corporate governance—that pervasive
incapacity of organisations to cope with the expectations of
their constituents, is now an overwhelming factor
worldwide.’

‘It has indeed become a matter of sound corporate
governance. Something that demands leadership integrity
throughout the organization. The demands from businesses,
in the role occupational health, safety and environmental
risk management will play to create a successful result on
the bottom line, is also increasing by the day.’

Sasol—Sasol One Site and Foskor Ltd received their 29th
NOSCAR award. Somchem—Somerset West (a division of
Denel), received their 27th NOSCAR and Naschem (a
division of Denel) and Alpha Cement (Pty) Ltd—Roodepoort
Factory both received their 26th NOSCAR. SA Breweries,
Division of Denel, received their 25th NOSCAR and Somcement
Mining, Eskom, Lever Ponds and De Beers were some of the other NOSCAR
award recipients.

A total of 77 NOSCARS was presented to companies that
demonstrated a ninety five percent or more score during the
NOSA audit, in addition to recording a Disabling Incident
Frequency Ratio of less than one over the twelve-month
period.

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Mintek renews licensing agreement with AspenTech Africa*

The hydrometallurgical Processing Group within Mintek, one of the world’s leading technology providers specializing in mineral processing, extractive metallurgy and related fields, has renewed its licensing agreement with AspenTech Africa for the use of the AspenTech Engineering Suite. The contract is for a period of five years, while the two organizations have had a business partnership since 1996.

In addition, Mintek has pioneered the use of software in the hydrometallurgical area, developing their own internal training courses and support for organizations requiring simulation in the metallurgical field.

The Aspen Engineering Suite comprises of specific software products that are integrated to provide workflow-based solutions to the process industries. The software provides solutions for asset optimization by providing the foundation for teams to work co-operatively with compatible systems and methodologies, as well as to quickly evaluate project alternatives for financial, process and schedule viability. In addition, improvement in operating margins efficiency and throughput and the ability to achieve additional visibility into the current state of operations, while leveraging company specific knowledge, are noted.

‘The contract with AspenTech was renewed due to the product’s technical superiority and value for money over other competitive offerings in the arena,’ says Roger Kusch of Mintek.

‘Mintek’s aim is to enable the minerals industry to operate more effectively by developing and making available the most appropriate and cost-effective technology,’ says Kusch.

‘By continuing with our relationship with AspenTech and employing the use of the AspenTech Engineering Suite in our Hydrometallurgical Processing Group, we will be able to continue to meet our goals,’ Kusch says.

‘Mintek presented a paper at the AspenTech Africa annual conference held earlier this year and since then there have been several requests for more information about hydrometallurgical process simulation,’ says Dr Ralph Grob director, business consulting, AspenTech Africa.

‘Together, AspenTech and Mintek will proceed to follow up on these opportunities,’ concludes Grob.

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* About Mintek
  Mintek is one of the world’s leading technology providers specializing in mineral processing, extractive metallurgy, and related fields. Working closely with industry and other research organizations, Mintek offers R&D expertise, service testwork, equipment, and novel process technologies for the precious metals, base metals, ferro-alloys, and industrial minerals sectors worldwide. Mintek’s aim is to enable the minerals industry to operate more effectively by developing and making available the most appropriate and cost-effective technology. They are engaged in the full spectrum of minerals research, from the mineralogical examination of ores to the development of extraction and refining technologies, the manufacture of end products, and feasibility and economic studies. Much of this work is carried out in close liaison with the minerals and metallurgical industries, both locally and internationally. For more information, visit www.mintek.co.za

* About AspenTech
  Aspen Technology, Inc. provides industry-leading software and implementation services that enable process companies to increase efficiency and profitability. AspenTech’s engineering product line is used to design and improve plants and processes, maximizing returns throughout an asset’s operating life. Its manufacturing/supply chain product line allows companies to increase margins in their plants and supply chains, by managing customer demand, optimizing production, and streamlining the delivery of finished products. These two offerings are combined to create solutions for Enterprise Operations Management (EOM), integrated enterprise-wide systems that provide process manufacturers with the capability to dramatically improve their operating performance. Over 1 500 leading companies already rely on AspenTech’s software, including Aventis, Bayer, BASF, BP, ChevronTexaco’s, Dow Chemical, DuPont, ExxonMobil, Fluor, Foster Wheeler, GlaxoSmithKline, Shell, and TotalFinaElf. For more information, visit www.aspentech.com