Ultra-deep mining: The increased potential for squeezing conditions

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Synopsis

This study reviews the concept of squeezing (large time-dependent deformation) in rock and investigates the possibility of this phenomenon becoming more pronounced in the planned ultra-deep mines of the South African gold mining industry. Although squeezing behaviour is not commonly found at the current depths of the gold mining industry, it is observed at Hartebeestfontein Mine due to a combination of weak rock and high stresses. Calculations based on the average strength of the Witwatersrand quartzites and the competency factor used to identify squeezing conditions in civil engineering tunnels, indicate that there is an increased risk of squeezing behaviour in ultra-deep mines. This will adversely affect the profitability of these mines and highlights the need for further research into the time-dependent behaviour of rock. Finally, the current support strategies in squeezing conditions are reviewed.

Introduction

The depletion of shallow ore reserves is forcing the South African gold mining industry to exploit reefs at ever-increasing depths. It is forecast that by the year 2010 some 30% of the South African gold production will come from depths greater than 3000 m (Johnson and Schweitzer[1]). Of significance are recent discussions of planned ultra-deep mining operations at depths between 3500 m and 5000 m (Gürtunca[2], Diering[3], Johnson and Schweitzer[1], Schweitzer and Johnson[4]). As the estimated vertical virgin stress at these depths will vary between 95 MPa and 135 MPa (assuming a rock density of 2700 kg/m^3), there is no doubt that the challenges facing the industry are immense. As these excavations will be the first attempt ever in the world to mine at these great depths, there is no guarantee that the current rock mechanics knowledge and associated empirical rules will ensure viable ore extraction. The need for research into suitable technologies and mining methodologies is now probably more pressing than ever. To address these issues, a collaborative research programme called 'Deepmine' was recently established (Gürtunca[2]). This is a joint effort between CSIR Division of Mining Technology (Miningtek), the gold mining industry, government, tertiary education institutes and the Foundation for Research Development (FRD). Diering[3] discussed a number of critical technologies needed for viable mining operations at these depths. Rapid horizontal access development and support of these tunnels so that they remain open for their planned life-time are two of the crucial issues. A phenomenon that is relatively unknown in the South African gold mining industry is the occurrence of squeezing rock conditions in tunnels. In some civil engineering tunnels, squeezing conditions lead to severe problems that require specialized excavation techniques and expensive support installation. As will be discussed in this work, there is an increased potential for squeezing conditions in ultra-deep mining that may put additional strain on the profitability of these mines. This paper will describe the phenomenon of squeezing, discuss examples of this behaviour at Hartebeestfontein mine and explain why it may become more prominent in ultra-deep mining. Existing support methodologies in squeezing conditions are also reviewed.

Squeezing behaviour

Changes in the local stress state due to mining activity perturb the stability of the rock mass surrounding excavations. The subsequent readjustment of the rock towards a new equilibrium does not occur instantaneously but as a time-dependent process. This process can include two types of inelastic deformation, namely slow creep-like movements and

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rockbursts. Depending on the rock type and stress, excavations can show a propensity towards either of these two phenomena. Although it is an active field of research, the conditions associated with the transition from stable deformation to rockbursting are not yet fully understood. In relation to mine safety, it is preferable that all deformation occurs in a non-violent fashion. Excessive time-dependent rock movement is however undesirable as it strongly affects the long-term stability of underground openings. Significant creep-like movement of the rock is termed *squeezing behaviour*. This results in large tunnel convergence with severe support difficulties. The importance of understanding this phenomenon was underlined by the ISRM who established a commission on squeezing rocks (Barla[5]). The definition of squeezing as proposed by this commission is:

> 'Squeezing of rock is the time-dependent large deformation which occurs around the excavation, and is essentially associated with creep caused by exceeding a limiting shear stress. Deformation may terminate during construction or continue over a long period'.

When a tunnel is driven into soft squeezing rock (such as soft clays or mudstone), the ground advances slowly into the opening without visible fracturing or loss of continuity (Gioda and Cividini[6]). Squeezing can however also involve different mechanisms of discontinuous failure of the surrounding rock. Possible mechanisms are complete shear failure in rock if the existing discontinuities are widely spaced, buckling failure in thinly bedded sedimentary rocks and sliding failure along bedding planes (Aydan *et al.*[7]). The magnitude of tunnel convergence, the rate of deformation and the extent of the failure zone depend on the geotechnical conditions and the magnitude of stress relative to rock mass strength. Of interest is that rockbursting is not associated with squeezing (Barla[5]). In this context 'rockbursting' probably refers to strain bursting and not to major damage resulting from large shear type events on geological structures. The creep deformation acts as an efficient redistribution mechanism of stress, preventing the build-up of large stresses close to the excavation and thereby reducing the incidence of strain bursting. In a mine subjected to squeezing conditions, larger shear type seismic events may however still be possible due to global stress changes affecting the stability of geological structures such as faults and dykes.

Squeezing conditions at Hartebeestfontein Mine

An example of squeezing rock conditions in the South African gold mining industry can be found at No 6 shaft, Hartebeestfontein Mine in the Klerksdorp area (Malan and Bosman[8]). Mining operations at Hartebeestfontein Mine mainly expose the quartzitic members of the Main Bird (MB) Series which forms part of the Witwatersrand Supergroup. The uniaxial compressive strength of some of these members can be as low as 130 MPa. The overall competency of the rock mass and its ability to provide stable mining excavations for prolonged periods appears to be greater in the quartzites encountered in the vicinity of Ventersdorp Contact Reef and Carbon Leader mining operations in other parts of the Witwatersrand basin. These quartzites are less bedded and substantially more siliceous than those present at Hartebeestfontein Mine. As a result of this greater strength, the rock in other mines would seem to be more susceptible to strain bursting under high stress conditions.

The combination of weak quartzites and high stress at Hartebeestfontein Mine leads to appreciable time-dependent movement of the rock. This is most notable in service excavations located in highly stressed ground where the rock becomes progressively more fractured with time. Tunnel closure rates in the order of 50 cm per month have been observed, leading to severe support difficulties. In stopes, movements of up to 6 cm per shift can be observed. The problems caused by the time-dependent rock movements at this mine were highlighted in a research study (Piper and Wagner[9]) to evaluate the long-term stability of an underground refrigeration complex at No 6 shaft of the mine. It was suggested in this study that the long-term stability of the refrigeration chamber could not be assured even with the upgrading of the support system. Further measurements and extensometer data showed an acceleration of chamber closure as the No 6 shaft pillar became progressively more isolated (Roberts and Jager[10]). It was, however, unclear at that stage how much of this behaviour was caused by true time-dependent behaviour and how much by an increase in stress due to far-field mining activity. With deteriorating conditions, the refrigeration chamber was eventually relocated to overstoped ground.

The squeezing mechanism at Hartebeestfontein Mine is considered to be a combination of time-dependent failure of the intact rock and sliding along bedding planes. The quartzites of the Main Bird Series are well bedded with bedding thickness in the range of 0.1 to 1.3 m (King *et al.*[11]). Appreciable shear slip and dilation of the bedding planes have been noted (Roberts[12]). The buckling of layers close to the excavation may also play a role.

Figure 1 illustrates the typical bulging of the haulage profile caused by the slow time-dependent processes in the rock. Significant footwall heave is also noticeable. With further deformation, the support eventually fails leading to the destruction illustrated in Figure 2. This necessitates frequent rehabilitation of the tunnels. If the time-dependent processes could be better understood, optimum strategies

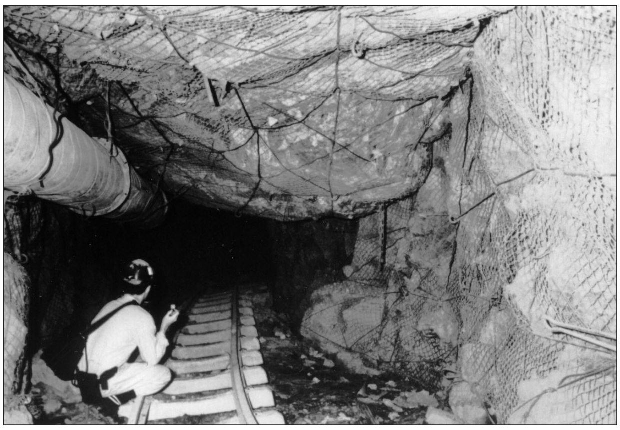

Figure 1—Haulage conditions experienced in the sqeezing rock at Hartebeestfontein mine (courtesy W.D. Ortlepp). The highly fractured nature of the rock is caused by slow time-dependent processes and not rockburst damage

could be developed to reduce the cost of the continuous rehabilitation and installation of new support. As an illustration of the costs involved, in a particular section of this mine, mining is impossible without constant rehabilitation of the access ways leading to the reef. Besides the development cost and the cost of initial support work, the rehabilitation of excavations is estimated to cost R2.4 million (US$540 000) per annum in 1997 terms (Malan and Bosman[8]). Although the loss of revenue due to production losses is difficult to quantify, this is conservatively estimated at R11 million per annum. Nevertheless, the benefit of this squeezing behaviour is that strain bursting is virtually absent in this area. It should, however, be noted that these severe squeezing conditions are not encountered often at the current depths of the South African gold mining industry.

To illustrate typical rates of closure in squeezing tunnels at the mine, data from a measuring station in the 78A24 East haulage in the No 6 shaft area is illustrated. It would be of interest to measure tunnel closure on the surface of the excavation, but due to the poor rock conditions, closure pegs, which are not anchored deep in the rock, are lost very soon after installation. Therefore, the measuring station consisted of 2.2 m rods grouted in the hangingwall and sidewalls and a 0.4 m rod grouted in the footwall (Figure 3). The closure measurements were taken between the ends of these rods

Figure 2—Adverse haulage conditions at Hartebeestfontein mine caused by large time dependent deformation and the eventual collapse of the support. Note that this is not rockburst damage (courtesy W.D. Ortlepp)

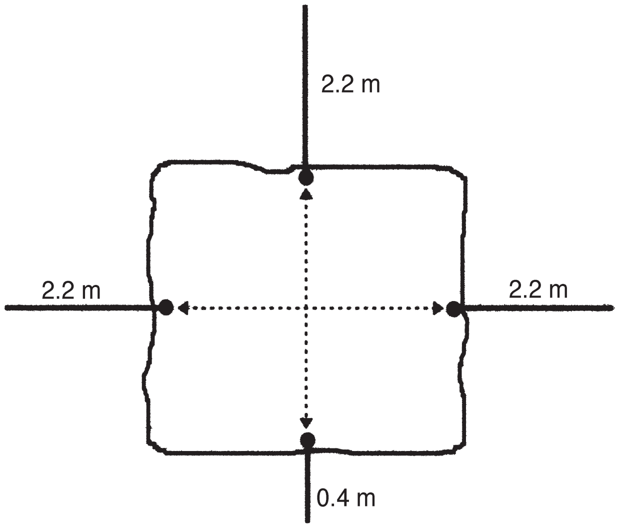

Figure 3—Closure station consisting of rods grouted deeply in the rock. Measurements were taken between the rods in the hangingwall and the footwall and the two rods in the sidewalls

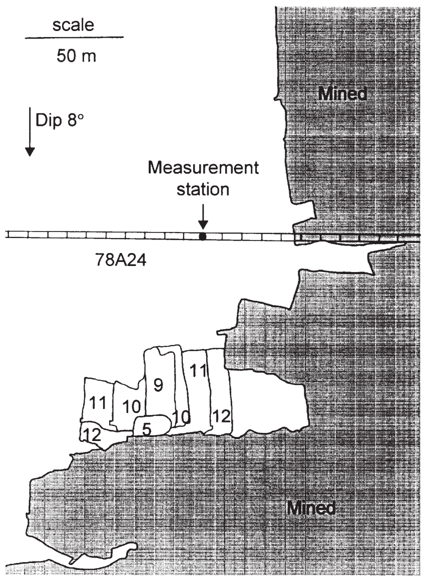

Figure 4—Plan view of the stoping operations surrounding the measurement station. The haulage is approximately 45 m below the reef at a depth of 2339 m below surface. The numbers indicate the month in which the particular section was mined in 1996

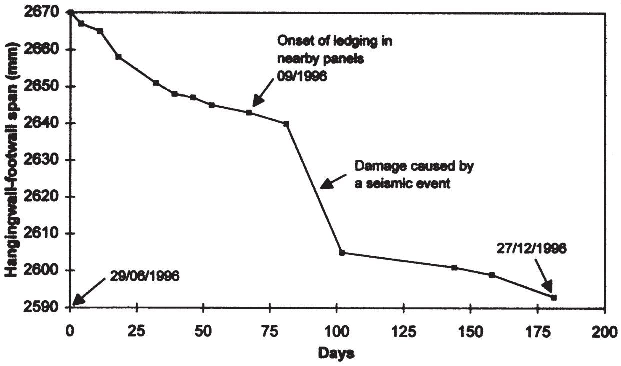

Figure 5—Vertical closure measured in the haulage

which protruded from the rock. The position of the measuring station in relation to the surrounding stoping operations is illustrated in Figure 4.

Measurements over a period of 180 days are illustrated in Figures 5 and 6. Closures of 77 mm and 65 mm were measured between the hangingwall and footwall and the two sidewalls respectively over this period. For the first 75 days of measurement, there was no mining nearby as the ledging in Figure 4 only initiated in September 1996. For this initial period, average closure rates of 0.4 mm/day and 0.24 mm/day were measured between the hangingwall and footwall and the two sidewalls respectively. Note that the magnitude of closure recorded is less than the surface deformation of the excavation because the measuring rods were anchored deeply in the rock. Malan and Bosman[8] showed that the majority of rock deformation occurs within the first two metres of the excavation walls. Measuring rods anchored deeply in the rock will therefore underestimate the surface deformation. Of importance, is that the magnitude of closure measured at this site is unacceptably high for a service excavation that needs to remain stable for many years. Note that the rapid increase in closure rate in September 1996 was not only due to the nearby mining, but also damage caused by a seismic event (magnitude 1.5) which was located approximately 200 m from the measurement station.

The increased risk of squeezing conditions in ultra-deep mines

For tunneling in soft rock, an empirical rule frequently used to identify squeezing conditions is the competency factor *c*. This is defined as the ratio of the uniaxial compressive strength of the rock to the vertical overburden stress (Muirwood[13], Nakano[14], Barla[5], Aydan *et al.*[7]).

$$c = \frac{\sigma_c}{\rho g H} \qquad [1]$$

where σ_c = uniaxial compressive strength of intact rock specimens
ρ = density of the rock
g = gravitational acceleration
H = depth below surface

In general, squeezing conditions are found for $c < 2$. This number was recently confirmed by Aydan *et al.*[7] who did an extensive survey of squeezing tunnels in Japan. The depth of tunnels in this study was less than 400 m and the host rock comprised typical soft types like mudstone, tuff, shale and siltstone. It is therefore unclear if this simple rule can be extended to ultra-deep mining in hard rock. In Figure 7, a competency factor of $c = 2$ (ρ 2700 kg/m^3, g = 9.81 m/s^2) is plotted on a graph of uniaxial compressive strength versus depth. Any combination of rock strength and depth below this line (called the squeezing line) may lead to squeezing conditions. Conditions also become progressively worse the further below this squeezing line the tunnel is situated. As mentioned above, the validity of the initial portion of the squeezing line (< 400 m) is confirmed by the many investigations of squeezing behaviour in soft rock (Aydan *et al.*[7]). To illustrate the increased potential for squeezing conditions in ultra-deep mines, this line is extended to 5000 m. The average strength of the Witwatersrand quartzites is 200 MPa (Gay and Jager[15]). At the current depths of the industry (< 3500 m), most tunnels developed in virgin ground are located above the squeezing line and will therefore appear stable. Of particular concern, however, is that for the ultra-deep mines, the average rock strength of 200 MPa is below the squeezing line. Figure 7 therefore suggests that a significant increase in the number of squeezing tunnels in ultra-deep mines can be expected. In planning the layouts of ultra-deep mines, access development should therefore be

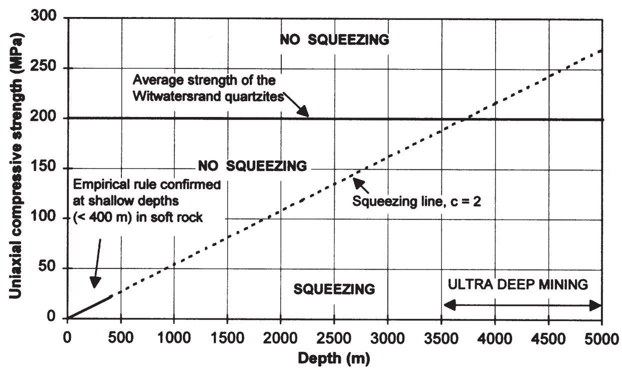

Figure 7—Hypothetical potential for squeezing conditions of ultra-deep mining excavations in hard rock. Squeezing conditions are expected everywhere below the squeezing line

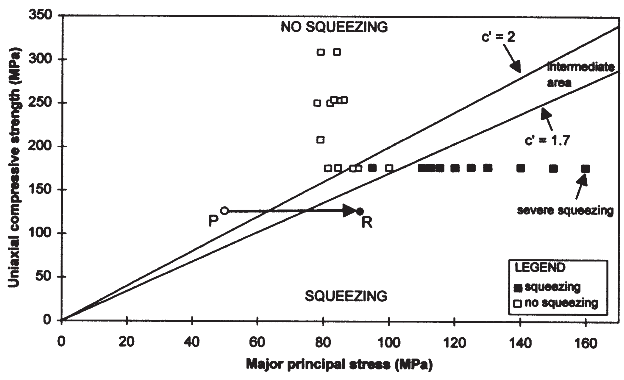

Figure 8—Squeezing conditions at Hartebeestfontein Mine (also see Appendix A). Points P and R are not real data points but are included to illustrate the increasing potential for squeezing conditions in rock with a particular strength as the major principal stress increases due to nearby mining or increasing depth (see text)

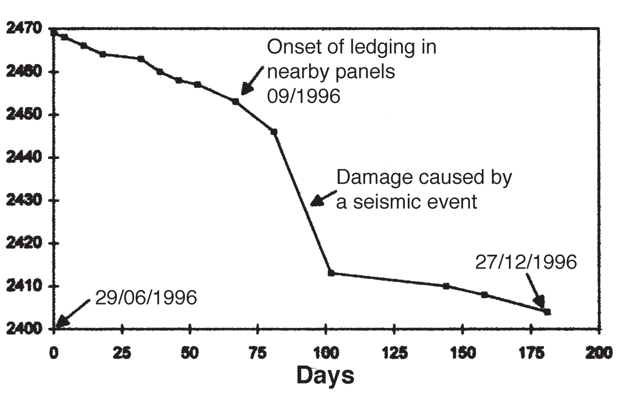

Figure 6—Sidewall closure measured in the haulage

located as far as practically possible in the more competent strata. It should, however, be emphasised that there is currently little evidence of squeezing in hard rock at great depths apart from the conditions at Hartebeestfontein Mine (see Figure 8 for some experimental data). Significant further work will be necessary to validate the applicability of the competency factor in hard rock at great depths.

For an isolated tunnel such as a civil engineering tunnel through a mountain, the *in situ* stress does not vary as a function of time. It is therefore relatively easy to predict squeezing conditions beforehand, using equation [1] or other suitable measures, and plan an effective support strategy. Unfortunately in a mining environment, the stresses acting on a particular tunnel may be constantly changing due to nearby mining activity. A tunnel or service excavation that is initially stable can start behaving in a squeezing fashion later in its life due to subsequent mining-induced stress increases. For a mining environment, equation [1] should be rewritten to use the actual stress rather than the estimated vertical virgin stress ρgH. It is not clear at this stage what the role of the intermediate and minor principal stresses are. As an illustration of the increasing potential for squeezing in remnant areas, equation [1] is modified to include the major principal stress σ_1 giving

$$c' = \frac{\sigma_c}{\sigma_1} . \qquad [2]$$

Consider a hypothetical tunnel developed in rock with a uniaxial compressive strength of 130 MPa (point P in Figure 8) and a major principal stress of 50 MPa acting on the tunnel. Squeezing conditions are again assumed to occur for a competency factor $c' < 2$. This is illustrated in Figure 8. At this stage the tunnel is above the squeezing line and will appear stable. If the major principal stress increases to 90 MPa due to extensive stoping in the surrounding area, the tunnel might start showing signs of instability as it is below the squeezing line (point R in Figure 8). The reverse effect is also possible for service excavations developed in overstoped ground. The magnitude of major principal stress is lower in these areas and therefore the excavations are located above the squeezing line.

Some experimental data points from Hartebeestfontein Mine are included in Figure 8. Appendix A contains further information regarding the tunnels surveyed for these data points. To identify squeezing conditions, the ISRM definition for squeezing given earlier in this paper was the initial consideration. As this definition is rather subjective, a further rule applied to the tunnels at Hartebeestfontein Mine is that only those that required frequent rehabilitation due to large time-dependent movements were identified as squeezing. The major principal stress for each data point was determined using an elastic MINSIM analysis. All the tunnels identified as squeezing were located in the MB6 quartzites with an average laboratory σ_c of 177 MPa. Variations in σ_c within this series was not accounted for, resulting in the data points lying in a straight line in Figure 8. It is clear that squeezing becomes more prominent for lower competency factors. It was also noted that the severity of squeezing increases with increasing distance below the squeezing line. This is similar to an observation made by Aydan *et al.*[7]. There appears to be an intermediate area on the graph where it will be difficult to predict squeezing conditions using equation [2]. It was observed at Hartebeestfontein Mine that squeezing conditions definitely occur for a competency factor $c' < 1.7$. This value should be seen in light of the rules used to identify squeezing conditions and also the fact that an average value of σ_c was used. This work needs to be extended in future by determining exact values of σ_c in the laboratory for each data point. It was mentioned earlier that for ultra-deep mining, a vertical virgin stress of 135 MPa is expected at a depth of 5000 m. It follows from the work in Figure 8 that a rock strength of at least 260 MPa is needed at these depths to ensure stable tunnel behaviour in virgin ground. In areas of extensive mining, even stronger rock will be needed.

It should be noted that σ_c in equations [1] and [2] refer to the strength of intact laboratory specimens and not the strength of the rock mass that can be weakened by bedding planes and joints. These equations should probably be rewritten to include a rock mass rating. Steiner[16] found that squeezing conditions are influenced by the rock type (lithology), strength of the rock mass, orientation of the rock structure, stress state, water pressure, construction techniques and support systems. Of these factors only one stress component and the intact rock strength are included in equations [1] and [2]. As a possible improvement to these equations, the rockwall condition factor[17] (RCF) (commonly used as tunnel support design criteria) should be investigated as a tool to predict squeezing conditions. The RCF is given by

$$RCF = \frac{3\sigma_1 - \sigma_3}{F\sigma_c} \qquad [3]$$

where σ_3 is the minor principal stress and F is an empirical rock mass condition factor. For competent rock, $F = 1$. For very weak rock, in which bedding planes are spaced less than 0.1 m apart, an appropriate value of F is approximately 0.5. It is known that conditions deteriorate rapidly for RCF > 1 requiring increased levels of support resistance. As $\sigma_3 = k\sigma_1$ (where k is the ratio between major and minor principal stress), equation [3] can be written as

$$RCF = \frac{(3-k)\sigma_1}{F\sigma_c} . \qquad [4]$$

It is interesting to note that for competent rock ($F = 1$) in a stress field where the k-ratio is unity, equation [4] reduces to

$$RCF = \frac{2\sigma_1}{\sigma_c} . \qquad [5]$$

For RCF = 1 (the onset of unstable conditions), this becomes

$$0.5 = \frac{\sigma_1}{\sigma_c} . \qquad [6]$$

When inverting this equation, it is similar to equation [2] where a competency factor of 2 signifies the onset of squeezing conditions. For these specific conditions ($F = 1$, $k = 1$) it appears that RCF=$1/c'$. The RCF factor might, therefore, be a more flexible tool in mining environments to predict squeezing conditions for different values of F and k.

One mechanism that may contribute to the time-dependent failure processes in squeezing conditions is the creep of intact rock (Figure 9). Although the creep rate of intact hard rock is low (see Figure 10) and it does not contribute significantly to the tunnel closure, it can nevertheless lead to the time-dependent failure of rock that is loaded below its short-term failure strength. The formation of many creep fractures will contribute greatly to the closure and instability of the tunnel. Figure 10 illustrates the laboratory creep rate of different hard rocks in the South African gold mining industry under uniaxial loading conditions (Malan[18]). The elastic and strength properties of these rocks are given in Table I. For all the rock types tested, the creep rate increases with increasing stress. Note that for rocks with higher uniaxial compressive strengths, larger stresses are required to obtain the same creep rate. As explained below, the time to failure for the rock types also decreases as the applied stress increases.

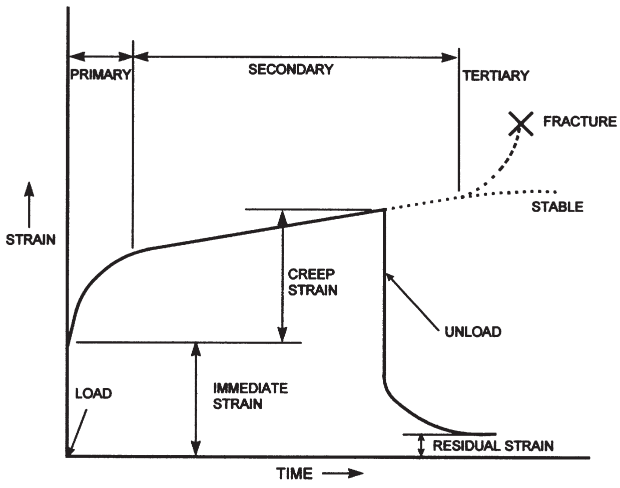

Figure 9—Typical creep response of intact rock subjected to a constant load smaller than the failure strength of the rock (Malan[18])

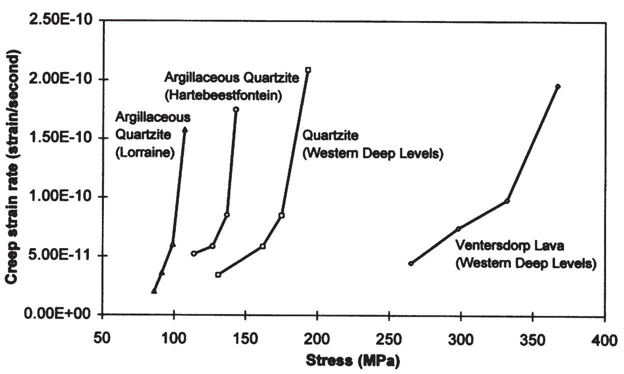

Figure 10—Effect of stress on the strain rate of the secondary creep phase (see Figure 9) of different hard rocks in the South African gold mining industry (Malan [18])

Table I

Average values of elastic and strength properties for the rocks given in Figure 10. The abbreviations are: σ_c=uniaxial compressive strength, E=Young's modulus, ν=Poisson's ratio

Rock type	σ_c (MPa)	E GPa)	ν
Argillaceous quartzite (Lorraine gold mine)	107	60	Unknown
Ventersdorp Lava (Western Deep Levels)	436	88	0.26
Quartzite (Western Deep Levels)	237	79	0.13
Argillaceous quartzite (Hartebeestfontein Mine)	142	72	0.26

Kovács[19] investigated the relationship between time to failure (t_F) and applied load (σ_t) for samples of quartzite with $\sigma_L < \sigma_t < \sigma_c$ where σ_L is the long-term strength and σ_c the uniaxial compressive strength. The long-term strength is the stress below which failure will never occur regardless of the time of load application. The following empirical relationship was used to represent this relationship.

$$t_F = a\left(\frac{1}{i} - 1\right)^b \qquad [7]$$

where

$$i = \frac{\sigma_t - \sigma_L}{\sigma_c - \sigma_L} \qquad [8]$$

For argillaceous quartzite, the calculated values of *a* and *b* were 24.75 and 1.95 respectively (for t_F calibrated in hours). From equations [7] and [8], the time to failure will therefore decrease as the ratio of applied stress to uniaxial compressive strength increases. This could possibly explain why Aydan *et al.*[7] found that the elapsed time for the recognition of squeezing phenomena varies with the competency factor of the rock. The smaller *c* in equation [1] (and therefore the larger the ratio of applied stress to uniaxial compressive stress and the smaller the time to failure) the quicker the squeezing behaviour is noted. In ultra-deep mines, the creep rate of the intact rock will increase and the time to failure for creep fractures to form will drecrease. This serves as further evidence that squeezing behaviour in the ultra-deep mines might become more prominent. Regarding seismicity, this increased creep activity might be beneficial as it helps to dissipate some of the stored strain energy in a non-violent fashion.

Support of tunnels in squeezing rock

In civil engineering tunnels, two different support methodologies are commonly used in squeezing conditions, namely an active and a passive approach (Barla[5]). An *active approach* consists of the installation of very heavy linings to provide rigid support. An example of this type is the thick masonry lining used in the Simplon tunnel at the Italian-Swiss border in 1906 (Steiner[16]). The liner was 1.67 m thick to protect the tunnel of 3 m diameter. More recently steel sets in combination with thick concrete linings have been used as active support. To control the squeezing rock in the Sidi Mezghiche tunnel in Algeria, the support consisted of steel sets at 1 m spacing and 40 cm of shotcrete. A final concrete lining of 65 cm was also installed (Panet[20]). Pre-reinforcement of the rock is another active method. In heavy squeezing rock, an active support approach is, however, not always successful. The low deformability of steel, concrete and shotcrete in these conditions can lead to buckling of the steel units and shearing of the linings. In the Frejus tunnel which links France and Italy through the Alps, the large tunnel closure resulted in bending of the steel ribs and rupture of the shotcrete (Panet[20]). *Passive approaches* on the other hand, attempt to accommodate the large deformations without the support collapsing. This approach may include yielding rock bolts which allow significant deformation without failure, over-excavation where the tunnel is excavated to a larger size allowing for significant closure to take place and delayed installation of shotcrete to allow the squeezing energy to be dissipated first by another passive yielding support system. A popular passive technique is to include longitudinal compression slots in the shotcrete to prevent a build-up of load in the lining that would lead to failure. This is illustrated in Figure 11. Schubert and Blümel[21] described the successful use of thin shotcrete linings with longitudinal gaps in combination with dense rockbolt patterns to control the squeezing rock in tunnels in the eastern Alps.

Diering[3] emphasised the important role that shotcrete may play in the support of tunnels in ultra-deep mines. Kirsten and Bartlett[22], however, found that in squeezing conditions, shotcrete is loaded quickly to above its failure strength and may be destroyed unless the thickness is extremely large. A solution would then be to use the passive approach of compression slots in the shotcrete as illustrated in Figure 11. The effectiveness and financial implications of this approach in a mining environment should, however, be carefully investigated. Flexible membrane support such as Everbond (Wojno and Kuijpers[23]) is another possible alternative. A flexible membrane provides broken rock with an increased residual strength, even when subjected to large deformation. This allows for the efficient build-up of load-carrying capacity in the fractured rock with the benefit of increased tunnel stability. These membranes have the added benefit that they seal the rock against ingress of fluids which would otherwise contribute to the time-dependent failure processes (see Lama and Vutukuri[24] for the effect of water on rock creep).

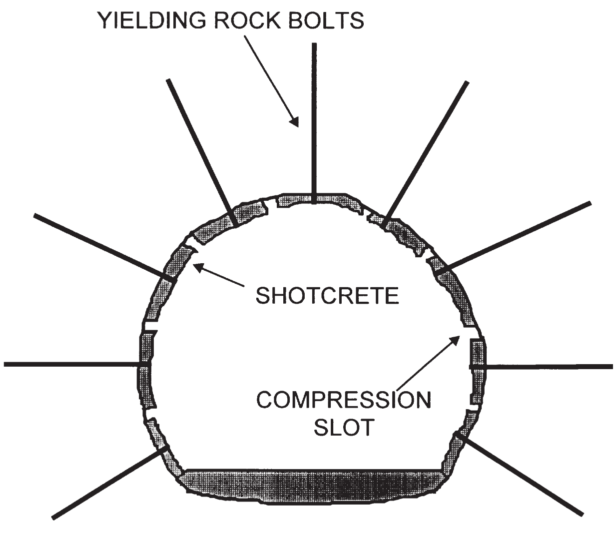

Figure 11—Compression slots in the shotcrete to accommodate large deformation

It is clear from the squeezing tunnels at Hartebeestfontein Mine that typical haulage support consisting of anchors and wiremesh and lacing is not effective in controlling the large time-dependent deformations (Malan and Bosman[8]). From observations and closure measurements, it nevertheless appears that 2.2 m anchors with areal support, such as wiremesh and lacing, bind the fracture zone surrounding the excavation into a quasi-coherent structure which, to some degree, resists and abates the massive deformation. Once this structure is broken, either by massive support failure or intentional bleeding to increase the cross-sectional area of the excavation, deformation becomes uncontrollable. Unfortunately failure of the structure is a reality at some point in the life of the excavation. Once failure has taken place and support rehabilitation is complete, the process has been observed to repeat itself. Investigations of numerous collapses have revealed that only approximately 50% of the anchors failed. Anchors predominantly fail in tension, although occasional shear failure is observed. The effect of support on excavation stability is shown by the fact that deformation in most cases is evident in the footwall first, where no support is installed. In areas where 6 m long 400 kN anchors have been installed, the closure rate appears to be less than in areas where only 2.2 m smooth bars were used. Yielding anchors have been installed in excavations without significant benefit. It appears that any support that is capable of binding the fracture zone into a more coherent structure delays catastrophic failure, but not indefinitely. It may be that the flat dipping bedding planes result in a poor interaction between the rock bolts due to the sub-parallel rock layers in the sidewall (Haile[25]). The stability of the excavation may therefore be more a function of the capacity of the mesh and lacing than of the type of anchors used. As mentioned above, membrane support systems and shotcrete with compression slots may play a role in further delaying or even preventing these collapses.

Haile[26] described a support strategy that appeared to be successful in a squeezing tunnel at Kloof gold mine. The tunnel was developed at a depth of approximately 3000 m in rock characterized by a high frequency of bedding planes with infilling which resulted in a low rock mass strength. The support strategy consisted of the immediate application of a 25 mm shotcrete layer and primary bolting as close as possible to the development face. Approximately 15 m behind this face, additional support was installed consisting of a 75 mm steel fibre-reinforced shotcrete layer, secondary bolting and wiremesh and lacing. This appeared successful in controlling the deformation, although it should be noted that the financial costs were high. This particular strategy highlights the importance of timing of support installation in potential squeezing conditions. If too much time elapses before the installation of support, the rock may undergo unravelling making it more difficult to control (Steiner[16]). Pan and Dong[27] and Pan and Huang[28] analysed the effect of time of support installation in squeezing rock by assuming that the rock behaves in a viscoelastic fashion. Results indicate that earlier support installation ensures a lower tunnel convergence. This is, however. accompanied by higher support pressures (Cristescu *et al.*[29]; Sakurai[30]) which may lead to rapid failure of the support in heavy squeezing rock as explained above.

Conclusions

This study reviewed the concept of squeezing rock conditions in tunnels and investigated the possibility of this phenomenon becoming more pronounced in ultra-deep mines. As tunnels developed in squeezing rock undergo large time-dependent deformation, it is difficult and expensive to support these excavations. Due to the relatively weak nature of the rock mass at No 6 shaft, Hartebeestfontein Mine, severe squeezing behaviour is noted in some tunnels in the shaft pillar area at a depth of 2500 m. Of concern is that the existing support methodologies are unable to control the time-dependent deformation effectively and expensive rehabilitation of these tunnels is constantly required. From a study of squeezing tunnels in civil engineering construction, it appears that the ratio of uniaxial compressive strength to overburden stress (the competency factor) is a useful measure to predict squeezing behaviour in tunnels. An analysis using this competency factor and an average value of uniaxial strength for the Witwatersrand quartzites, indicated that there will be a marked increase in the number of squeezing tunnels in the planned ultra-deep mines of the gold mining industry. As this will put further strain on the profitability of these mines, further research into the conditions leading to squeezing behaviour in hard rock should be conducted as a matter of urgency. Time-dependent failure processes in the rock are the fundamental mechanisms underlying squeezing behaviour and research efforts should be focused on this. A preliminary understanding of the time-dependent behaviour has already been achieved in the SIMRAC (Safety in Mines Research Advisory Committee) project GAP332 'Deep Gold Mine Fracture Zone Behaviour' (Malan *et al.*[31], Malan[18]) and is currently being investigated further. Apart from the benefits of understanding the long-term stability of service excavations better, it also provides an understanding of the time-dependent stress transfer processes and the accompanying seismicity in deep level mines (Napier and Malan[32]). This allows the effect of mining rate and mining policies such as full calendar mining to be investigated.

Regarding squeezing behaviour, it is important to address the following issues.

1) Is the competency factor (or RCF factor) a reliable measure to predict squeezing behaviour in deep hard rock mines?
2) What are the mechanisms controlling squeezing behaviour in hard rock?
3) How can the layouts be optimized to allow for access development in the most competent strata? Experience at Hartebeestfontein Mine illustrated that it is beneficial to locate important service excavations such as pump and refrigeration chambers in the low stress areas of overstoped ground.
4) What is the optimum support strategy for squeezing tunnels in hard rock? In civil engineering construction, it appears that a combination of yielding rock bolts and shotcrete, with compression slots to accommodate large deformations, is successful. The effectiveness and cost implications of this support type should be tested in a mine that is already subjected to squeezing behaviour such as Hartebeestfontein Mine. The potential role of flexible membrane support such as Everbond should also be investigated.

To conclude, it should be emphasised that in addressing these issues, it is important to gain a fundamental understanding of rock deformation mechanisms and specifically those leading to squeezing behaviour in hard rock. As the financial investment in ultra-deep mining will be enormous, it is important that strategic design decisions are not solely based on empirical design criteria.

Appendix A

The tunnels investigated for squeezing conditions are located in the No 5 and No 6 shaft areas of Hartebeestfontein Mine (see Figures 1A and 2A). The following tunnels provided the data used in Figure 8 with the information summarized in Table IA. The major principal stress for each case was calculated using a MINSIM analysis. The elastic parameters used were Young's modulus = 50 GPa, Poisson's ratio = 0.2 and the vertical stress gradient = 0.027 MPa/m. The k-ratios were 0.5 in both directions.

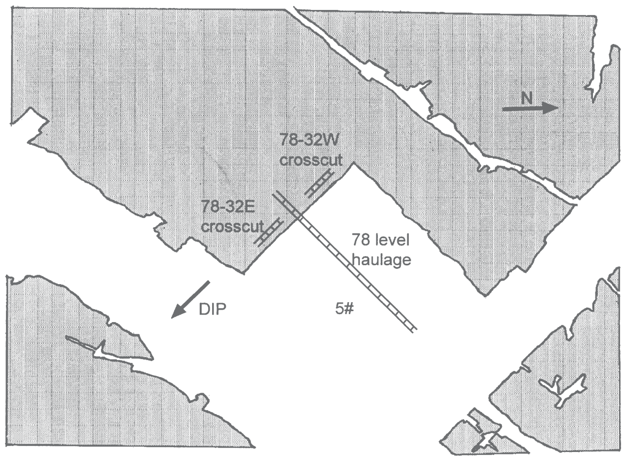

Figure 1A—Plan view of the mining geometry in the No 5 shaft area and the locations of the tunnels included in this study

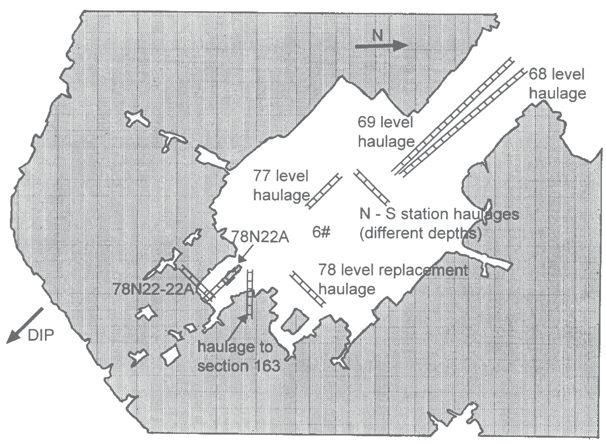

Figure 2A—Plan view of the mining geometry in the No 6 shaft area and the locations of the tunnels included in this study

Table IA

Tunnels surveyed at Hartebeestfontein Mine to investigate the relationship between competency factor and squeezing conditions

Location	sc (MPa)	s1 (MPa)	c´	Strata	Squeezing
5# 78-32E crosscut	177	84	2.1	MB6	No squeezing
5# 78-32E crosscut	177	89	2.0	MB6	No squeezing
5# 78-32W crosscut	177	112	1.6	MB6	Squeezing
5# 78 level haulage	177	90	2.0	MB6	No squeezing
5# 78 level haulage	177	100	1.8	MB6	No squeezing (local FOG areas)
5# 78 level haulage	177	110	1.6	MB6	Squeezing (onset of squeezing)
5# 78 level haulage	177	120	1.5	MB6	Squeezing
5# 78 level haulage	177	130	1.4	MB6	Squeezing
6# 78N22-22A crosscut	177	140	1.3	MB6	Squeezing
6# 78N22-22A crosscut	177	160	1.1	MB6	Squeezing (large deformation)
6# 78 replacement haulage	177	95	1.9	MB6	Squeezing
6# 78 replacement haulage	177	115	1.5	MB6	Squeezing
6# 78 replacement haulage	177	120	1.5	MB6	Squeezing (support ineffective)
6# haulage to Section 163	177	110	1.6	MB6	Squeezing
6# haulage to Section 163	177	125	1.4	MB6	Squeezing
6# 78N22A crosscut	177	110	1.6	MB6	Squeezing
6# 78N22A crosscut	177	150	1.2	MB6	Squeezing
6# 68 level haulage	250	82	3.0	GE6	No squeezing
6# 69 level haulage	308	84	3.7	GE7	No squeezing
6# 77 level haulage	254	83	3.1	MB7	No squeezing
6# 68 station haulage	250	78	3.2	GE6	No squeezing
6# 69 station haulage	308	79	3.9	GE7	No squeezing
6# 71 station haulage	209	79	2.6	MB2	No squeezing
6# 75 station haulage	177	81	2.2	MB6	No squeezing
6# 77 station haulage	254	84	3	MB7	No squeezing
6# 78 station haulage	254	85	3	MB7	No squeezing
6# 80 station haulage	254	86	3	MB7	No squeezing

5# 78-32E crosscut

Although this crosscut is situated below an abutment, conditions in the tunnel are good with no signs of squeezing. The average middling is 53 m. This crosscut is supported with shepherd crooks, mesh and lacing on a 1 m pattern. It is planned to install 6 m full column grouted cable anchors on a 2 m pattern in future.

5# 78-32W crosscut

This crosscut is on the updip side of the reef and therefore deeper into the footwall. The average middling was 73 m. Conditions in this crosscut are much worse than in 78-32E with definite signs of squeezing visible. The support consists of shepherd crooks, mesh and lacing on a 1 m pattern.

5# 78 haulage

Prominent squeezing can be seen in some areas. It appears that squeezing is observed in this haulage for a competency factor of less than 1.7. This haulage is supported with shepherd crooks, mesh and lacing on a 1 m pattern and 6 m cable anchors on a 2 m pattern.

6# 78N22-22A connecting crosscut

The first part of this crosscut is overstoped resulting in very good conditions. For the rest of this excavation, conditions started to deteriorate as the major principal stress increased to more than 110 MPa. The tunnel was abandoned when the stress was approximately 200 MPa. The squeezing rate in this tunnel was very high and in excess of 500 mm/month in some areas. The support consisted of shepherd crooks, mesh and lacing on a 1 m pattern.

6# 78 replacement haulage

This haulage was developed on the same elevation as the original 78 level haulage, but updip and therefore deeper in the footwall. Squeezing is nevertheless observed throughout the whole excavation. It appears that this excavation was developed in a less competent layer of the MB6 quartzites as the bedding is pronounced with small bedding thicknesses. This haulage is supported with shepherd crooks, mesh and lacing on a 1 m pattern and 6 m cable anchors in some areas on a 2 m pattern.

6# haulage to section 163

The entire length of this tunnel is badly damaged with squeezing visible. Regular rehabilitation is still taking place in some areas. The support consists of shepherd crooks, mesh and lacing on a 1 m pattern.

6# 78N22A connecting crosscut

This crosscut was developed for a second tramming route (one route in use while the other is being rehabilitated). Squeezing conditions are visible along the entire length of this crosscut with rehabilitation work done on a regular basis. This crosscut is still open, although it is subjected to the same stress magnitude as the 6# 78N22-22A connecting crosscut that was abandoned. The support consists of shepherd crooks, mesh and lacing on a 1 m pattern.

6# 68 level haulage

This haulage is situated in the northwest haulage pillar. It cuts through different layers of rock as it is situated on the dip of the strata. Conditions in this tunnel are very good with minimal scaling visible. The support, consisting of rockstuds and mesh, appears to be adequate.

6# 69 level haulage

This haulage is also situated in the northwest haulage pillar with conditions and support similar to the 6# 68 level haulage.

6# 77 level haulage

This haulage is situated in the shaft pillar. Some limited movement is seen in this haulage, but it cannot be described as squeezing yet. The support consists of shepherd crooks, mesh and lacing on a 1 m pattern.

6# 68 level station haulage (north shaft to south shaft)
6# 69 level station haulage (north shaft to south shaft)

Both these haulages are in good condition with no mobilized fracturing visible in these areas. Support consists of shepherd crooks, mesh and lacing on a 2 m pattern. There are also cable anchors installed in some areas.

6# 71 level station haulage (north shaft to south shaft)

The 71, 72 and 74 level station areas are more fractured than the other levels. Buckling of the steel guides in the No 6S shaft are experienced in these areas as a result of the sidewall movement in the shaft. A possible reason for this behaviour is the highly bedded nature of the rock in these areas. These haulages are supported with shepherd crooks, mesh and lacing with a 1 m pattern and cable anchors with a 4 m pattern. Rehabilitation work was needed in some areas, but this is not done as frequently as for those tunnels identified as squeezing.

6# 75 level station haulage (north shaft to south shaft)

Conditions in this haulage are as good as those on 68 and 69 levels. The haulage is supported with shepherd crooks, mesh and lacing on a 2 m pattern and cable anchors on a 4 m pattern.

6# 77 level station haulage (north shaft to south shaft)

Some scaling of the rock visible in the sidewalls and hangingwalls. The haulage is supported with shepherd crooks, mesh and lacing on a 2 m pattern and cable anchors on a 4 m pattern.

6# 78 level station haulage (north shaft to south shaft)

The rock is fractured with some bulging of the support in the hangingwall. The haulage is supported with shepherd crooks, mesh and lacing on a 2 m pattern and cable anchors on a 2 m pattern.

6# 80 level station haulage (north shaft area to south shaft)

Only the south shaft goes down to 80 level. This haulage is from the north shaft position (although the north shaft does not exist at this level) to the south shaft. There is some limited deformation taking place in some areas. The haulage is supported with shepherd crooks, mesh and lacing on a 1 m pattern and cable anchors in certain areas.

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Mintek technology opens the door for Gamsberg zinc project*

Mintek technology is once again assisting mining giant Anglo American Corporation to embark on a multi-million rand minerals development project in one of the poorest parts of the country. This is only five years after technology developed jointly by Mintek and Anglo American enabled the highly successful mega-million rand Namakwa Sands project to go ahead on the Cape west coast.

'The recent announcement by the Corporation of its plans to invest a total of R4 billion (in current money terms) in the Gamsberg low-grade zinc project in the northern Cape, is another example of Mintek's ability to fulfil its mandate to ensure South Africa's prosperity through the careful development and maximization of its vast mineral resources', says Mintek President, Dr Aidan Edwards.

According to Anglo American 'new technologies developed... by Anglo American metallurgists and Mintek should offer significant technical and cost benefits when applied to the project which will provide about 2000 jobs and provide an economic stimulus for the competitive supply of goods and services from domestic sources'. The Corporation believes that cash operating costs for Gamsberg, net of by-products credits, will be approximately 30c/lb zinc, making it one of the lowest cost zinc producers in the world.

According to Anglo American's New Mining Business Division chairman, Dr Bobby Danchin, 'it is the Corporation's intention to proceed rapidly with the evaluation of new technology alternatives, one of which is based on the use of DC plasma-arc smelting techniques similar to those applied successfully at our Namakwa Sands operations at Saldanha, and we will be extending this technology to the treatment of high-grade zinc concentrates in a joint programme with Mintek. We will embark upon small-scale exploratory testwork immediately and will undertake a major pilot plant campaign at Mintek towards the middle of 1999. The feasibility study, including the testwork at Mintek, will cost about R85 million and is due for completion by the end of 1999', says Dr Danchin.

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