Time-dependent tunnel deformation at Hartebeestfontein Mine

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Synopsis

The problems associated with squeezing rock conditions in tunnels are well known and have been extensively investigated in the past. Although squeezing conditions are predominantly found in tunnels developed in weak rock types it has been noted at the No. 6 Shaft of Hartebeestfontein Mine where the host rock consists of hard, brittle quartzites. This paper investigates typical time-dependent deformation mechanisms in the rock at Hartebeestfontein Mine.

The paper will focus on observations made in a strike-orientated tunnel that intersected weak quartzite layers, that were sandwiched between two competent quartzite beds. The observed squeezing mechanism is dominated by creep along bedding planes with a soft talcaceous infilling that behaves in a clay-like fashion when saturated in water. Stress-induced deformation processes, some distance into the sidewall of the excavation, force the already fractured periphery of the excavation into the void.

A laboratory study of the creep of intact rock and discontinuities collected at this site was conducted to characterize the time-dependent behaviour. The difference in creep rates between the two types of quartzite found at this site is described in the paper. Creep tests performed on the talcaceous infilling material found that its presence allows substantial shear creep along discontinuities.

Attempts were also made to simulate the squeezing mechanism observed underground with numerical techniques. Due to the discontinuous nature of the mechanism described above, a viscoplastic displacement discontinuity technique was used as it allowed for the explicit simulation of discontinuity creep. The results of the modelling and how it compared with the observed behaviour are described in the paper.

Environmental impact statement

The work described in this paper will not cause any new, or contribute to any existing, hazards confronting the environment.

Introduction

Hartebeestfontein Mine is situated in the Klerksdorp gold fields, which is located on the north-west rim of the Witwatersrand Basin. The mine exploits the Vaal reef, which is situated in the Central Rand Group of the Witwatersrand Supergroup. Massive time-dependent deformation (squeezing) is mainly observed in quartzites, which is situated in the Stilfontein and Strathmore formations of the Johannesburg subgroup. More particularly squeezing has been noted in the MB3 member of the Strathmore formations and the MB6 member of the Stilfontein formation (see Figure 1). The case under review in this paper is situated in the MB6 member in the north-west side of the mine.

The upper contact of the MB6 can be found approximately 30 m below the Vaal reef and is 80 m thick. The MB6 quartzite can be described as an upper grey to honey coloured argillaceous quartzite. Numerous grits, and small-to-medium pebbled conglomerates with shale, acid lava, chert, quartz and quartzite pebbles can be found in the MB6. The regularity and thickness of grit bands appear to be greater in the north and north-west side of the mine where the mine's No. 6 Shaft is situated. Bedding thickness in the MB6 ranges between 20 cm and 120 cm with well defined bedding contacts filled with soft shale-like material of varying thicknesses.

Hartebeestfontein Mine employ the scattered mining method and since its inception in 1952, has developed approximately 2000 km of tunnels. Main access haulages are situated 60 m in the footwall of the reef and are, therefore, mostly located in the MB6 member of the Stilfontein formation.

Excavations situated in the MB6 member in the deeper levels of the mine's No. 6 Shaft have been observed to deform at a steady rate until mining operations encroach. The stress changes brought about by encroaching mining operations accelerate the deformation to a point where constant rehabilitation is required to maintain the operational function of the excavation. Once stress has been relieved and rehabilitation is complete, it has been noted that some deformation still occurs albeit at a much reduced rate.

Evidence of the significant squeezing behaviour at the mine is clearly visible in the

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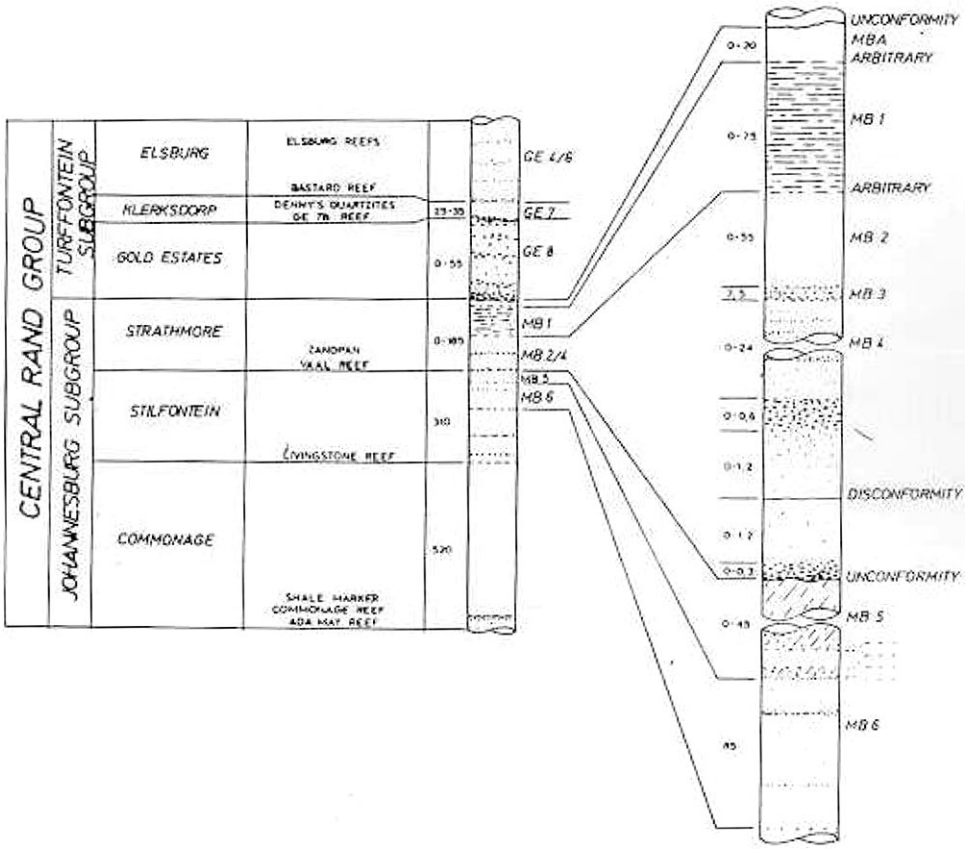

Figure 1—Stratigraphic column of Central Rand Group as found at Hartebeestfontein Mine

haulage closure measurements described in Malan and Basson[14]. This behaviour seems contrary to that expected for quartzite, as squeezing is mostly associated with soft rocks such as shale and mudstone. The importance of understanding this phenomenon was underlined by the ISRM who established a commission on squeezing rocks (Barla[3]). 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.'

The support problems caused by squeezing is well documented (e.g. Panet[19], Steiner[26], Gioda and Cividini[9], Schubert and Blümel[23]). In civil engineering tunnels, two different support methodologies are commonly used in squeezing conditions namely an active and a passive approach (Barla[3]). An *active approach* consists of the installation of very heavy linings to provide rigid support. In the early twentieth century, thick masonry linings were often installed in the tunnels to control the deformation (Steiner[26]). More recently steel sets in combination with thick concrete linings have been used as active support (Panet[19]). 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. *Passive approaches*, on the other hand, attempt to accommodate the large

Figure 2—Typical tunnel conditions prior to rehabilitation where squeezing is experienced (Ortlepp)

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. Schubert and Blümel[23] 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.

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[9]). Squeezing can, however, also involve different mechanisms of discontinuous failure of the surrounding rock. Possible mechanisms are complete shear failure in the rock if the existing discontinuities are widely spaced, buckling failure in thinly bedded sedimentary rocks and sliding failure along bedding planes (Aydan *et al.*[2]). From the study described in this paper, it appears that sliding failure along bedding planes is a dominant mechanism of the squeezing behaviour at Hartebeestfontein Mine. A study was undertaken at the mine to improve the understanding of the deformation mechanisms. The preliminary results of this study are described in the paper.

Site description

In a tunnel on the 78 Level (2367 m deep) of No. 6 Shaft, a squeezing mechanism dominated by the creep of bedding planes was recently observed. The 78 Level haulages were developed early in the life of the shaft when primitive stress conditions were prevailing. The primitive stress conditions were measured not far from the site under investigation. The following stress tensor depicts the stress environment as determined from stress measurements done by the borehole over coring method (Gay and v.d. Heever[7]).

$$\begin{vmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{vmatrix} = \begin{vmatrix} 41.573 & 4.762 & 4.676 \\ 4.762 & 50.551 & 1.375 \\ 4.676 & 1.375 & 66.876 \end{vmatrix} \; MPa$$

Support of the excavation was done in two phases. The primary phase was completed during the development of the tunnel and consisted of 2.2 m long 16 mm diameter rockstuds. Soon after the completion of the development secondary support in the form of 2.2 m long full column grouted smoothbar shepherds crooks with wiremesh were installed in a 1 m square pattern. Steel wire ropes were then threaded through the shepherds crooks to form a diamond grid of re-enforcing. Later this support was then further upgraded with the installation of 6 m long full column grouted rope anchors installed at a rate of six anchors every two metres.

The tunnel was incapacitated due to excessive closure which occurred prior and during over stoping operations. Sidewall to sidewall closure in excess of 1 m was measured prior to the commencement of rehabilitation operations. Once the highly fractured and crushed zone was removed by rehabilitation operations it was noted that the section of the tunnel orientated on strike intersected weaker quartzite beds, which were sandwiched between two more competent quartzite beds (see Figure 3). The frequency of stress-induced fractures in the weak beds are much greater than in the competent beds above and below it. The depths of fracturing are estimated to be as much as 6 m.

The discontinuities that delineate the beds are well defined and are filled with weak altered material. The thickness of the infilling material is between 1 cm and 10 cm and varies over short distances along the planes. Shear deformation which took place on the bedding planes during the massive deformation appear to have ground the bedding material into a fine powder. The ground material displays talcaceous properties and behaves in a clay-like fashion when saturated in water. Slickensiding could be observed in the ground material suggesting previous exposure to water and substantial dip slip shear deformation on the bedding planes. The infilling material is very well laminated, more particularly so where the thickness exceeds 5 cm. In these cases shear deformation appears to localize at the top and bottom quartzite contact grinding the material into a fine paste where water is present. Evidence of shear deformation could be seen on some of the lamination surfaces. However, these appear to be insignificant when compared to the scale of dislocation of the bedding planes. Where the planes are less than 5 cm wide the infilling material appear to be mechanically reworked by the shear deformation resulting in a freshly brecciated appearance. The distinct presence of slickensiding was still observed at the upper and lower quartzite contacts.

Petrography analysis of the infilling material revealed that the rocks comprise predominantly (95%) of matrix, consisting of fine-grained quartz (40%) and mica (60%). The micaceous material includes roughly equal proportions of muscovite and pyrophyllite. Within the matrix, large angular quartz grains (0.2–1.0 mm) and muscovite grains (0.1–0.5 mm) are present. These larger grains occur in roughly equal proportions. The muscovite grains are often slightly deformed forming lozenge shaped grains, commonly referred to as mica-fish. Figure 4 shows a deformed mica-fish that is commonly observed in the thin sections. Fractures are often observed to be associated with the mica-fish. Quartz grains

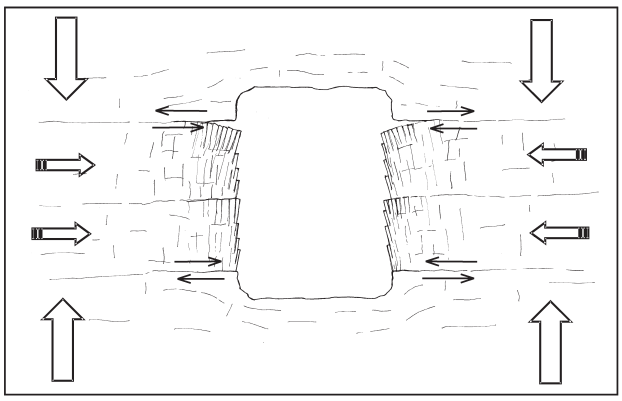

Figure 3—Idealized graphical representation of tunnel deformation

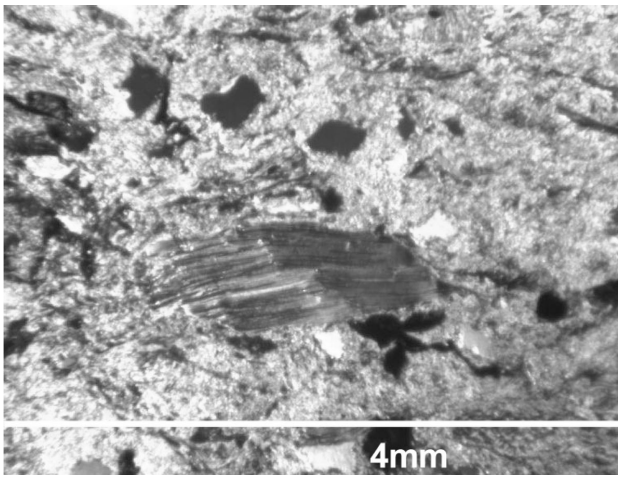

Figure 4—Thin sections showing deformed mica-fish in fine grained matrix (Steward[27])

adjacent to and surrounding fractures are not at all deformed whilst mica is often smeared out along edges of fractures indicating a more ductile component (Steward[27]).

Laboratory tests

In an attempt to understand the squeezing conditions observed in tunnels at the Hartebeestfontein Mine, laboratory tests were conducted on samples taken from the site previously described.

Uniaxial compressive and Brazilian tensile strength

Uniaxial compressive strength (UCS) and Brazilian tensile strength (UTB) tests were done on rock samples taken from the hangingwall and sidewall of the tunnel strata as these were observed to behave differently. Five UCS and five UTB tests were carried out on the two sets of samples. The average of the UCS obtained from the hangingwall was 180 MPa compared with an average UCS of 167 MPa for the samples taken from the sidewall. The average UTB of the hangingwall samples was 14.5 MPa and 18.5 MPa for the sidewall samples.

From observations of fracture depth and density in the two layers it was anticipated that the sidewall rock would be significantly weaker than the hangingwall rock. Contrary to this initial expectation laboratory tests showed that the intact strength of the two layers were very similar. It was observed that the sidewall was much more jointed, making it effectively weaker.

The above-mentioned test results were also used to estimate the Mohr-Coulomb parameters of the intact rock. The hangingwall strata has an estimated friction angle of 58° and a cohesion of 24.5 MPa compared with a friction angle of 55° and cohesion of 28.7 MPa for the sidewall strata.

Compression creep tests

Compression creep tests were conducted using the CSIR creep testing machine. This is similar to the machine described by Bieniawski1967. The machine uses cantilevers and deadweight to maintain a constant load over long time periods. Tests were done on specimens from the hangingwall and sidewall to compare the intact creep behaviour of the two strata. The tests were conducted in a climate-controlled laboratory with a constant temperature of 20°C and a relative humidity of 40%. The results can be seen in Figure 5 and indicate that the hangingwall has a steady state creep rate of 4.77×10^{-4} millistrain/hr compared to 7.56×10^{-4} millis train/hr for the sidewall.

The samples were loaded to ±90% of the ultimate failure load and the creep rate was determined between 20 and 50 hr of the creep cycle, which could be regarded as the secondary (steady state) creep phase. It was significant that the samples from the sidewall strata deformed at a creep rate 58% greater than that of the hangingwall strata.

Creep shear tests

Creep shear tests were conducted using the equipment and procedures described by Vogler *et al.*[29]. The tests were conducted using samples of ground infilling material previously described. The samples were collected from bedding planes at the site previously described. Of particular interest was the effect of moisture on the time dependent behaviour of an artificial smooth rock joint containing the ground infilling material. One test was conducted at a relative humidity of ±40% and a constant temperature of 20°C, while another was done with saturated gouge.

When saturated the joint had a friction angle of 14.1° compared with a friction angle of 19.3° at a relative humidity of 40%. The steady state creep rate of the joint with saturated filling was 4.392×10^{-4} mm/hr compared with 8.463×10^{-5}

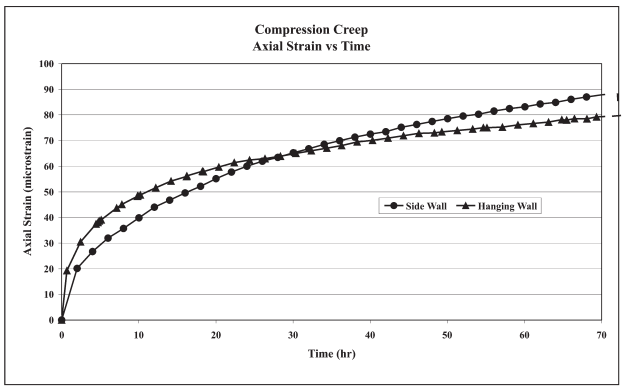

Figure 5—Graphs of compression creep test results

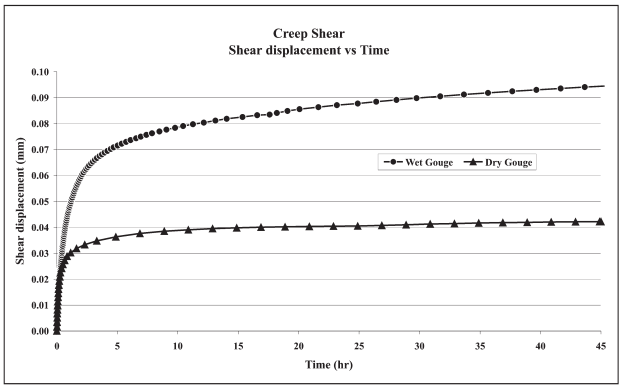

Figure 6—Graphs of creep shear test results

mm/hr at 40% relative humidity. It is significant to note that the steady state creep rate of the saturated sample is more than five times greater than the creep rate of the sample at 40% relative humidity.

The samples were loaded to ±80% of the peak shear strength and the creep rate was determined between 10 and 48 hr of the creep cycle, which can be regarded as the secondary creep phase.

Modelling the time-dependent failure processes in the rock

Introduction

To model the squeezing behaviour of tunnels, various approaches are described in the literature. Due to its simplicity, linear viscoelastic theory is popular as various combinations of the two principal states of deformation, namely elastic behaviour (represented by springs) and viscous behaviour (represented by dashpots), can describe complex strain-time behaviour with relative ease. Examples of this approach can be found in Gnirk and Johnson[10], Pan and Dong[18], and Malan[12]. There is some doubt, however, about the usefulness of this theory to represent time-dependent rock behaviour, as explained by Robertson[21], owing to the functional dependence of the viscosity values on stress, temperature and chemical environments. The biggest drawback of the theory is its inability to represent failure in the rock and it is, therefore, not suitable for simulating the squeezing behaviour at Hartebeestfontein Mine.

To include failure processes in rheological models, slider elements (also referred to as 'St. Venant' elements) are typically added to the elastic and viscous elements of viscoelasticity. These slider elements have specified failure strength and are immobilized below this strength. Commonly, a dashpot is placed in parallel with the slider to control the strain rate if the slider is loaded above its failure strength. This is the so-called 'Bingham' unit. Various combinations of elastic, viscous and St. Venant elements have been used by different researchers to simulate particular time-dependent problems. Gioda[8] and Gioda and Cividini[9] used a Kelvin unit in series with a Bingham unit to represent primary and secondary closure in squeezing tunnels. Tertiary movements can be considered by providing suitable laws relating to the values of the mechanical parameters (such as viscosity) to the irreversible part of the time-dependent strain. These rheological models are particularly suited for analysis carried out through the finite element method. This allows the interaction between squeezing rock and support to be simulated. Other examples of the use of these rheological models can be found in Akagi *et al.*[1], Song[25], Lee *et al.*[11], Euverte *et al.*[5], Sagawa *et al.*[22] and Nawrocki[17].

Since Perzyna[20] proposed the general concept of elasto-viscoplasticity, a number of workers have applied this theory to geological materials. Elasto-viscoplasticity is essentially a modification of classical plasticity theory by the introduction of a time-rate rule in which the yield function and plastic potential function of classical plasticity are incorporated. In comparison with viscoelasticity, a viscoplastic material shows viscous behaviour in the plastic region only. Examples of the application of this theory to time-dependent rock behaviour can be found in Desai and Zhang[4], Sepehr and Stimpson[24] and Swoboda *et al.*[28]. Fakhimi and Fairhurst[6] proposed a visco-elastoplastic constitutive model to simulate the time-dependent behaviour of rock. The model consists of an elasto-plastic Mohr-Coulomb model in series with a linear viscous unit and was implemented in an explicit finite difference code. Malan and Bosman[15] used a viscoplastic model with a time-dependent cohesion weakening rule to simulate the time-dependent rock behaviour at Hartebeestfontein Mine.

Although these viscoplastic models can simulate the time-dependent failure processes in the rock, it is based on a continuum approach and therefore has only limited application to the behaviour at Hartebeestfontein Mine where the creep of the bedding planes dominates. In an attempt to obtain a more realistic simulation of the creep processes, a discontinuum viscoplastic approach is investigated in this paper.

Model description

The detailed formulation of the viscoplastic displacement discontinuity model used in this study can be found in Napier and Malan[16]. In this model, it is postulated that the intact rock material behaves elastically and all inelastic behaviour, including viscoplastic effects is controlled by the presence of multiple interacting discontinuities. Shear slip on these discontinuities happens in a time-dependent fashion. This allows for the progressive redistribution of stress near the edges of mine openings. In particular, it is postulated that the rate of shear slip is proportional to the driving shear stress τ_e.

$$\frac{dD_y}{dt} = \varepsilon\kappa\tau_e \qquad [1]$$

Specifically where D_y is the displacement discontinuity in the shear direction, ε is a slip direction indicator and κ is a surface fluidity parameter (units of $m.Pa^{-1}.s^{-1}$) playing a similar role to the fluidity of classical viscoplastic theory. This formulation allows for the creep of the discontinuities including the bedding planes to be simulated. Napier and Malan[16] and Malan[13] used this model to simulate the time-dependent failure processes around tabular excavations. A good correlation between modelled and simulated stope closures were obtained in these studies. When setting up a particular model, the problem region of interest is covered by a specified mesh of potential crack surfaces. A random Delaunay mesh is used in this study with an example shown in Figure 7. At the end of each timestep, the stress distribution in the model is calculated. The program then searches through the potential crack surfaces and activate those that will fail according to the specified Mohr-Coulomb failure criterion. The activated discontinuities then relax according to Equation [1]. The resulting stress distribution will lead to the activation of further crack surfaces as the program steps through time. This continues until an equilibrium condition is attained (depending on the chosen model parameters).

Modelling results

Studying the effect of the bedding planes on the squeezing behaviour was the main objective of the preliminary modelling programme. A square tunnel with dimensions of

3.4 m was simulated. Two parallel bedding planes with a dip angle of 9°, intersecting the sidewalls of the tunnel, were included. The geometry used is simulated in Figure 7. The other parameters used in the simulation are given in Table I. It should be noted that the friction angles and cohesion are downgraded to simulate *in situ* conditions. Unfortunately, no time-dependent tunnel deformation measurements were available for this particular site and therefore arbitrary values for the surface fluidity were used in this preliminary modelling attempt. Although some criticism can be raised against the choice of parameters, it should be noted that the main purpose of the modelling was to investigate the suitability of the discontinuum viscoplastic model and to better understand the mechanism of squeezing at Hartebeestfontein Mine. If this approach is found successful, greater care should be taken in future to calibrating these parameters when attempting to predict future tunnel deformations.

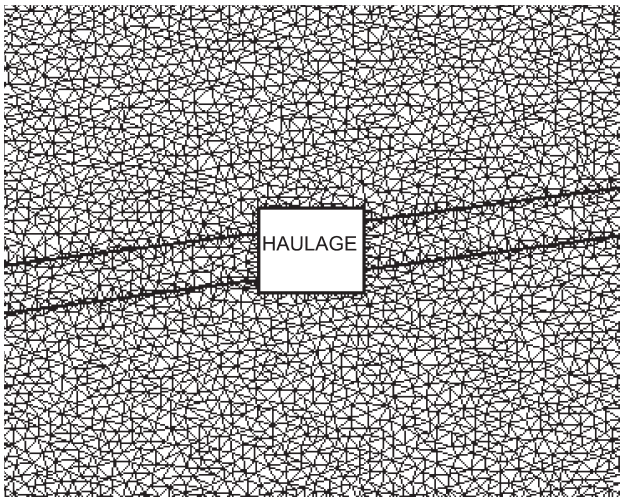

Figure 7—Random mesh of potential fracture surfaces surrounding the tunnel. The thick lines represent the bedding planes. It should be emphasized that these surfaces are initially intact and only those that fail according to the failure criterion are included in the solution process. Also, it should be kept in mind, that this is a boundary element formulation with infinite elastic boundaries. Although the potential fracture surfaces are only defined up to a certain distance from the tunnel, this should not be confused with a finite element or finite difference mesh

Table I

Modelling parameters used

Parameter	Value
Young's modulus	70 GPa
Poisson's ratio	0.2
Vertical stress	110 MPa
Horizontal stress	71 MPa
Properties of intact rock	
Intact friction angle	30°
Intact cohesion	20 MPa
Mobilized friction	30°
Mobilized cohesion	10 MPa
Surface fluidity	4 x 10^{-7} m.Pa.day
Properties of bedding planes	
Friction angle	5°
Cohesion	0 MPa
Surface fluidity	4 x 10^{-7} m.Pa.day

An important consequence of the imposed time-dependent displacement law imposed by Equation [1] is that the fracture zone surrounding the excavation does not form instantaneously but develops as a function of time. The discontinuities closer to the excavation fail first. They slip in a time-dependent fashion and gradually transfer the stress away from the tunnel where new fractures form. This is illustrated in Figure 8. As a result of this behaviour, the sidewall closure also behaves in a time-dependent fashion. This is illustrated in Figure 9. Note, however, that the indicated deformation is substantially less than that experienced underground. The bedding planes were only mobilized from the tunnel sidewalls up to approximately 3.6 m. Of interest is that the slip on the bedding planes is very low in spite of a low friction angle of 5°. This is illustrated in Figure 10. Contrary to what is observed underground, it appears that the bedding planes are not playing a dominant role in the deformation behaviour of the simulated tunnel or the fracture patterns. This is illustrated in Figure 11 where the fracture patterns for a tunnel with and without bedding planes are illustrated after a period of 149

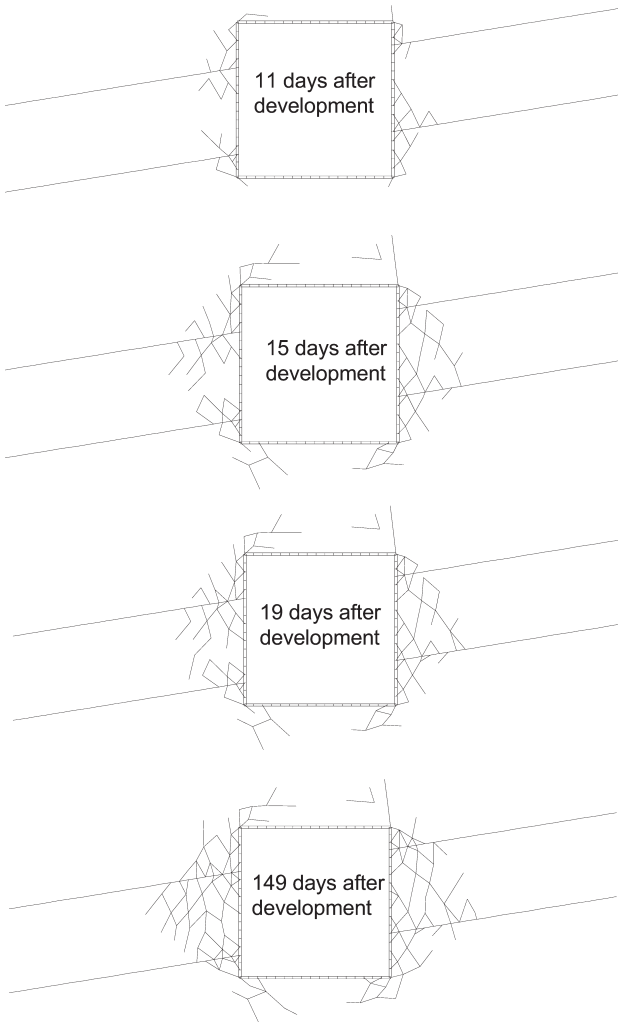

Figure 8—Time-dependent evolution of the fracture zone after development of the tunnel

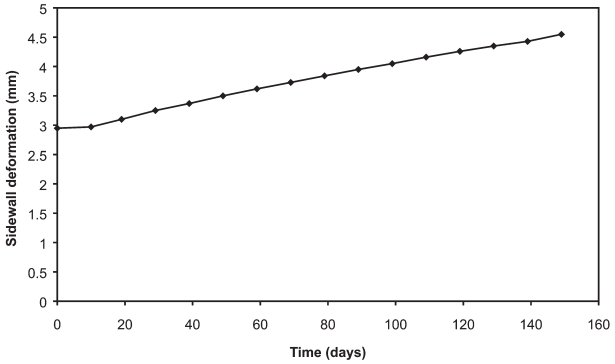

Figure 9—Time-dependent movement of the left sidewall. During this particular simulation, the slope of the graph during the first 10 days is small as the fractures were only allowed to initiate after day 10. This was done to allow the bedding planes to settle down

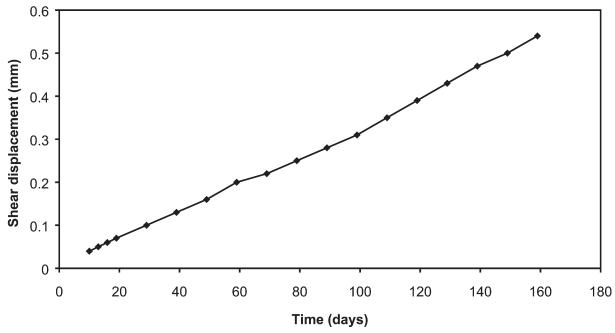

Figure 10—Shear slip of one of the upper right bedding plane as a function of time. This is the movement on the bedding plane at a distance of 0.8 m from the tunnel

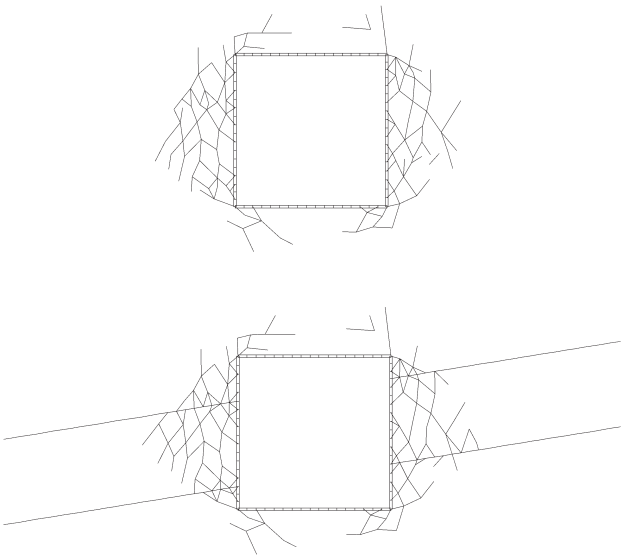

Figure 11—Fracturing around the tunnel for a model with and without bedding planes. Note that the fracture pattern is virtually identical

days.

Conclusions

Massive time-dependent deformation of main accessways at Hartebeestfontein Mine has resulted in substantial production delays and inflated tunnel rehabilitation and maintenance costs. An improved understanding of the deformation process could assist in considerable cost savings for the mine.

The tunnel deformation process appears to be driven by two mechanisms. The quartzite strata exposed in the sidewall of the tunnel is more susceptible to creep deformation than the more rigid hangingwall and footwall. The time-dependent fracture process occurring in the sidewall of the tunnel results in dilatational deformation into the excavation. Horizontal stresses resulting from resistance to dilatational deformation would normally arrest or inhibit further time-dependent deformation by confining the rockmass. The resistance to dilatational deformation may be as a result of increased frictional resistance due to clamped bedding or the action of the support system. The presence of bedding planes with low frictional resistance inhibits the generation of confining stresses and thereby allows greater horizontal freedom and therefore more time-dependent deformation.

Laboratory work has indicated that the presence of water on the bedding contacts may reduce the frictional resistance. Therefore, simply allowing water onto the bedding may activate and even accelerate deformation in the tunnel. Support systems appear to have very little effect on confining the fracture processes in the tunnel sidewall.

It appears from the investigation that the mechanical properties of the intact rockmass may have a lesser role in time-dependent deformation. The petrography and intact creep test results indicate that the presence of micaceous elements in substantial quantities may dictate the creep properties of a quartzite rockmass.

To simulate the time-dependent behaviour of the bedding planes and the rock mass at Hartebeestfontein Mine, a discontinuum viscoplastic model was investigated. The encouraging aspect of the model is that the fracture zone develops as a function of time resulting in the time-dependent deformation of the tunnel sidewalls. The deformation predicted by the model is however significantly less than that observed underground. A disappointing feature of the model is that there are only small movements on the simulated bedding planes which have little effect on the overall behaviour of the fracture zone surrounding the tunnel. When observing the large movements on the bedding underground, it appears from these preliminary results that the model is not yet capable of reproducing this behaviour. The effects of fracture mesh density and dilation of the fractures after failure should be investigated before any further conclusions are drawn. It is planned to use the laboratory shear creep results to assess the applicability of the constitutive law to model the shear creep behaviour of the bedding planes.

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OBITUARY

		Date of Election	Date Deceased
L D C Bok	Retired Fellow	28 February 1940	12 August 2000
B S Dykhouse	Retired Fellow	12 October 1956	15 May 2000
H J Swanepoel	Fellow	15 June 1990	March 2000