2017 FRANKLIN AWARD LECTURE

NUMERICAL MODELLING OF TABULAR EXCAVATIONS: OLD PROBLEMS AND NEW SOLUTIONS

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INTRODUCTION

It is a great honour to have been chosen as the recipient of the ISRM Franklin Award and I am grateful to the International Society for Rock Mechanics (ISRM) for bestowing this award on me. A keen interest of mine is the rock mechanics problems posed by the deep gold mines in South Africa. A large part of my past and current research efforts have been devoted to this topic as a result. This is certainly not a new rock engineering challenge as the tabular reefs of the Witwatersrand gold mines were discovered and exploited as early as 1886. The mines achieved record breaking depths in the decades that followed and the famous ERPM Mine achieved a depth of 11,003 feet or 3353 m below surface as early as 1958 (Cartwright, 1968).

Owing to the great depth and high extraction ratios, the industry suffered from the damage caused by rock bursts since the early days of mining. Documents such as the "*Report of the Witwatersrand Rock Burst Committee*" in 1924 attempted to classify the types of rock bursts and proposed mechanisms why these seismic events occurred (Mickel, 1933). Of particular interest is that the industry already conducted extensive underground measurements in 1927 to quantify the rock burst problem. Adler (1933) describes the measurements conducted at Crown Mines. A sketch of a primitive "sag-meter" to measure convergence in stopes is shown in Figure 1. The important aspect is that significant "creep-like" movements in the rock mass were recorded, even though the host rock mainly consisted of hard, brittle rock types such as quartzite (Figure 1).

In spite of the attempts to understand the rock burst problem, the design of the mining layouts was based largely on trial and error until the 1960's. A noteworthy change that occurred in 1941 was the implementation of the longwall mining method at ERPM (Figure 2) to reduce the formation of "remnants" or small blocks of isolated ground (Deane, 1954). These remnants were prone to bursting and the longwall method reduced the formation of these blocks.

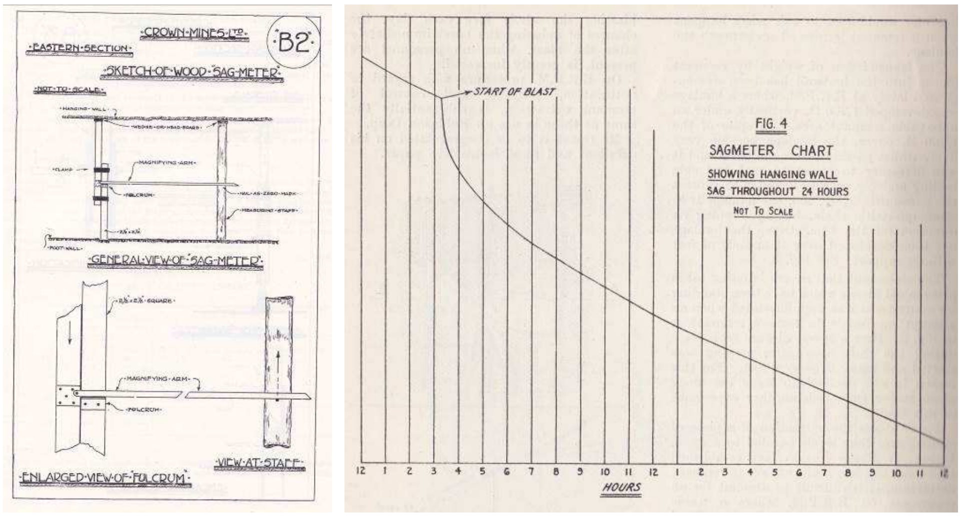

Figure 1. A sketch (left) of a primitive instrument to measure convergence in the South African gold mines in 1927 (after Adler, 1933). The graph on the right was recorded by an instrument that could record convergence in a continuous fashion. The convergence increases downwards. Note the creep in the rock mass after the blast occurred. This was recorded at Crown Mines in the early 1930's (after Hamilton, 1954) .

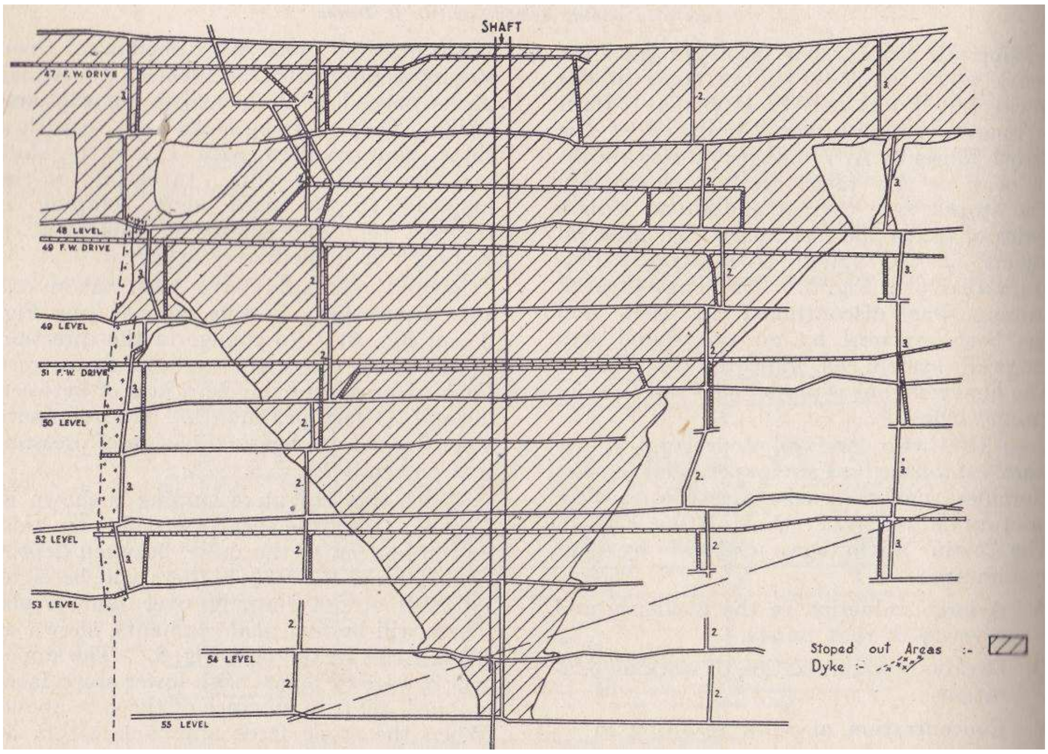

Figure 2. A plan view of the Hercules Longwall Area at ERPM Mine in 1943 (after Deane, 1954). The longwall method was introduced in 1941 at the mine to reduce the formation of small isolated blocks of ground or "remnants". The dip of these tabular orebodies was typically 25° to 35°. The great depth, high extraction ratio and the shallow dip of the orebody resulted in very high stress levels and seismicity ahead of the longwall faces.

THE ELASTICITY ASSUMPTION

Following the Coalbrook Colliery disaster in 1960, systematic rock mechanics research gained momentum in South Africa (Van der Merwe, 2006). This research was mainly done by the Chamber of Mines and the CSIR (Council for Scientific and Industrial Research). A key finding during those early years was that the rock mass, far away from the fracture zone surrounding the stopes, behaved in an elastic fashion. Ryder and Officer (1964) conducted measurements in a haulage situated in the hangingwall of the reef above two advancing longwalls over a period of a year (Figure 3). The section of haulage monitored was between 75 m and 120 m above the stoping excavations and therefore remote from the fracture zone surrounding the stoping excavations. Figure 4 illustrates the downward movement of the haulage and the simulated movement predicted by elastic behaviour. Based on these measurements, the authors concluded that:

- The rock mass at ERPM behaves essentially elastic.
- Elastic constants determined from small specimens appear to provide a realistic estimate of the properties of the solid rock underground.

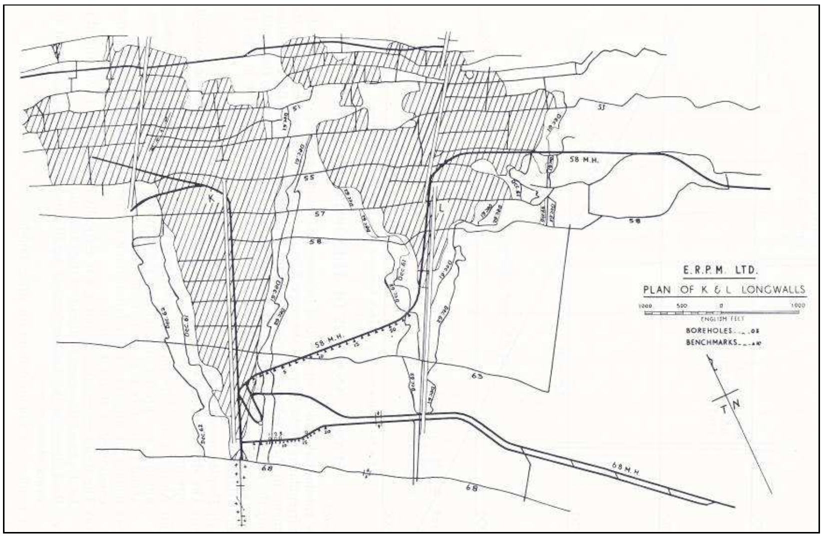

Figure 3. The K (left) and L (right) longwalls at ERPM Mine and the position of the 58 level hangingwall haulage where Ryder and Officer (1964) conducted measurements. This is a plan view of the mine workings.

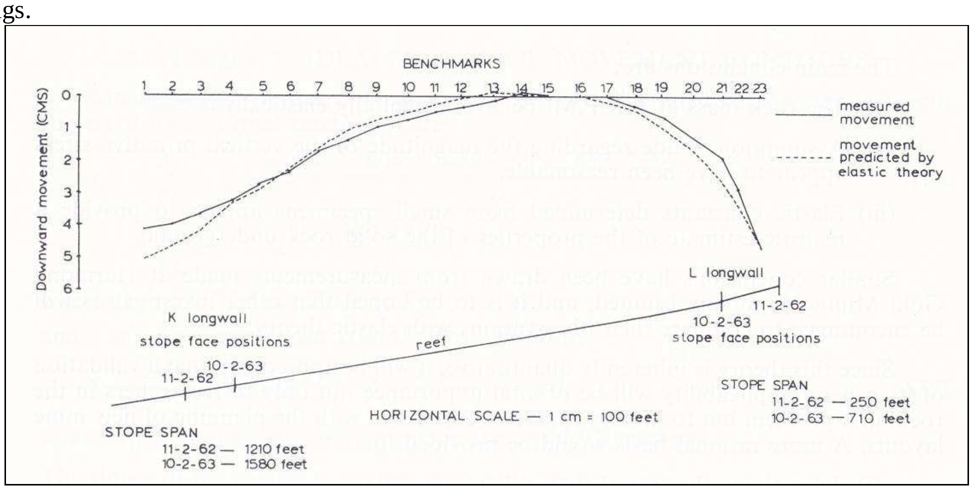

Figure 4. The famous measurements and elastic calculation by Ryder and Officer (1964) which indicated that the far-field rock mass behaviour can be approximated by elastic theory.

Building on this foundation of elastic theory, Salamon (1963, 1964) described the "face element" principle. This implied that if convergence and ride at each element of the mined area is known, stresses and displacements at any point in an elastic rock mass can be calculated. An integral equation can be set up to compute these convergences and rides, but computers were not readily available at the time to do these simulations. As a solution, it was illustrated that the Laplace equation governed the distributions of convergence and ride for tabular type stress problems. Since the same equation also governs the flow of electricity, an electrolytic tank stress analogue was constructed. This was a breakthrough as for the first time, stresses and displacements around a complex tabular excavation could be accurately determined.

As the electrolytic tank was difficult to set up, Cook and Schumann (1965) designed a practical electrical resistance analogue (Figure 5). A fixed 3D grid of resistors replaced the electrolyte and a patch board of earth pins made it easier to prepare the layout problem. A total of 10 of these analogs were constructed and the original Chamber of Mines model was upgraded as late as 1979.

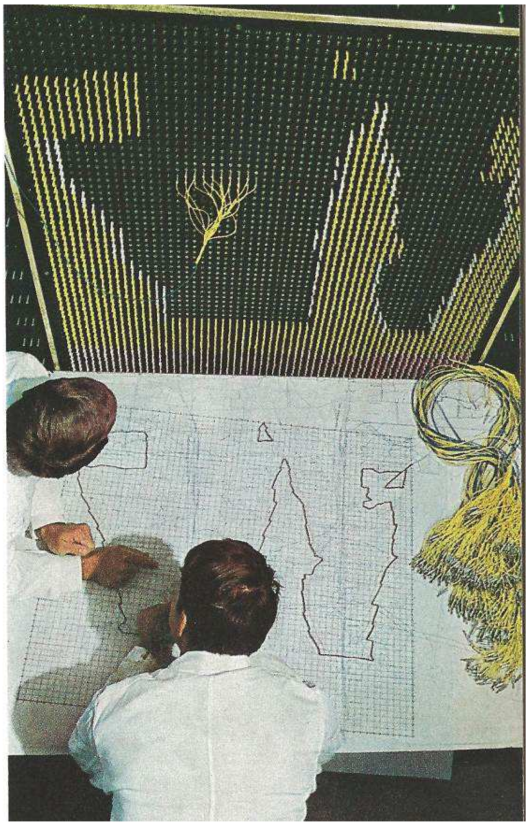

Figure 5. Engineers simulating a tabular layout using one of the electrical resistance analogue simulators.

Plewman et al (1969) and Deist (1972) described the first MINSIM (short for **Min**ing **Sim**ulator) type computer programme. This code was considered as a digital version of the electrolytic and resistance analogues developed earlier. Of interest was that the components of this first MINSIM refer to the "Tank generator" and the "Tank structure in memory". It typically solved a 64 x 64 element reef plane using the same principles described by Salamon (1963). This computer development was made possible when the University of the Witwatersrand acquired a computer with a faster processing unit and storage capacity than what was available in the rest of South Africa. The computer program was developed to avoid the cumbersome transfer of data from the analogues to a computer to calculate the off-reef stresses and displacements (which required a separate integration process). As described by Deist (1972), on the analogues, the reef plane was customarily represented by 60 x 60 discrete squares that were considered either fully mined or unmined. This necessitated the transfer of 3600 potentials for every solution. MINSIM was therefore the first complete digital solution of the tabular mining problem.

In 1981, the Chamber of Mines Research Organisation (COMRO) did a survey regarding the usage of MINSIM-type programs in industry. At that stage there were two distinct families of codes namely:

- MINSIMC: This was a descendant of SHAMIP, which was essentially similar to Deist's original MINSIM. MINSIMC had powerful features such as generalised co-ordinate systems and it could allow for a variable stoping width. Its main drawback was that it was non-portable and could only run on an IBM 370 computer.
- FREER/DREEF: This was developed by S.L. Crouch and extended by workers in South Africa. Many different versions of this code were available. Its big advantage was that it was transportable and could run on any large minicomputer or mainframe. In comparison to MINSIMC, it also had user-friendly graphic input-output features.

Based on this study, it was proposed that a completely new system be developed that could be run on a minicomputer. COMRO adopted a resolution in November 1981 that a modularised MINSIM-type system be developed. This development had to result in a transportable code and include a full multi-reef capability. The development and coding of this program was done by John Napier and the result was the MINSIM-D program (Figure 6).

Figure 6. Manuals of the historic MINSIM-D tabular simulation program.

The assumption of an elastic rock mass and the development of the modelling tools to simulate the irregular layouts of the tabular stopes resulted in a much improved engineering approach to design these layouts. Various design criteria such as Energy Release Rate (ERR), Average Pillar Stress (APS) and Excess Shear Stress (ESS) are routinely used to design these layouts (Ryder and Jager, 2002). A typical modern layout is shown in Figure 7 and it illustrates the dip pillars to control regional seismicity and bracket pillars to minimize the seismic events caused by large geological structures. This layout should be compared to the much older layouts shown in Figures 2 and 3.

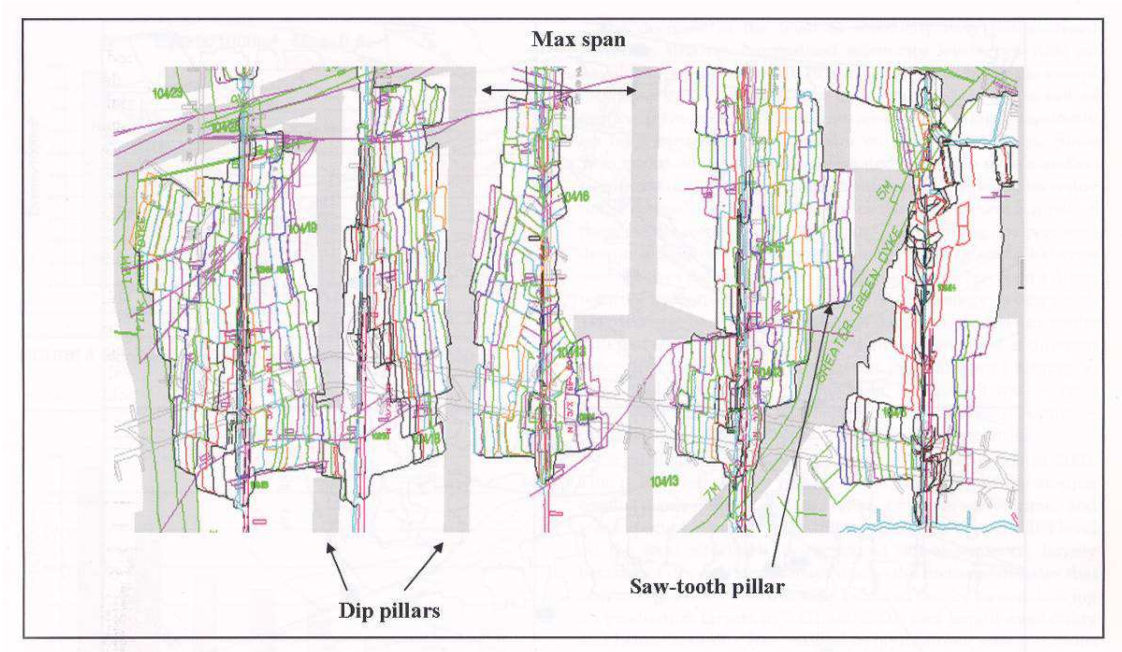

Figure 7. A typical modern layout of a deep South African gold mine to mitigate the risk of damaging seismicity (after McGill, 2007). This is a plan view of the orebody and excavations. The spans of the stopes are limited and large dip pillars (the grey bars - typically 30 m to 40 m wide) are included in the layout. The geological structures are clamped by so-called bracket pillars.

THE LIMITATIONS OF ELASTIC MODELLING

In spite of the major advances in tabular mine layout design after the introduction of the elastic codes, some practical problems cannot be simulated. Rock engineers working on these mines, for example, commonly use mining rate as a tool to control seismicity in high risk areas. The elastic codes cannot simulate the effect of mining rate, however. Mining rate needs to be studied in more detail as it is known that the rock mass undergoes significant time-dependent deformation in some geotechnical areas (Malan et al. 2007). This effect was in fact recorded as long ago as in the 1930’s (Figure 1). Another recent example is shown in Figure 8 to illustrate the significant “creep” component recorded in an intermediate depth tabular platinum mine. For the gold mines, it is proposed that the time-dependent convergence data may be useful to identify remnants that may be safely extracted. A difficulty faced with these studies is that no numerical tool readily exists that can simulate the time-dependent rock mass behaviour on a mine-wide scale. Although several types of commercial finite difference and finite element codes are available with built-in creep models, it is not practical to simulate the small mining steps of typically 1 m per blast in a tabular layout with these codes. The overall dimensions of these layouts can be in the order of kilometres in the strike and dip directions and therefore the displacement discontinuity boundary element approach is still preferred.

Although it seem attractive to use a simple viscoelastic model to simulate the behaviour shown in Figure 8, earlier work indicated that a viscoelastic model is not suitable to replicate the spatial behaviour of the convergence recorded underground (Malan and Napier, 2017). Viscoelastic theory cannot simulate the decrease in convergence rate as the distance to face increases (Figure 9). Recent studies have indicated that a limit equilibrium displacement discontinuity model with a time-dependent failure criterion may be useful to simulate on-reef time-dependent failure processes on a mine-wide scale (Napier and Malan, 2012; 2014).

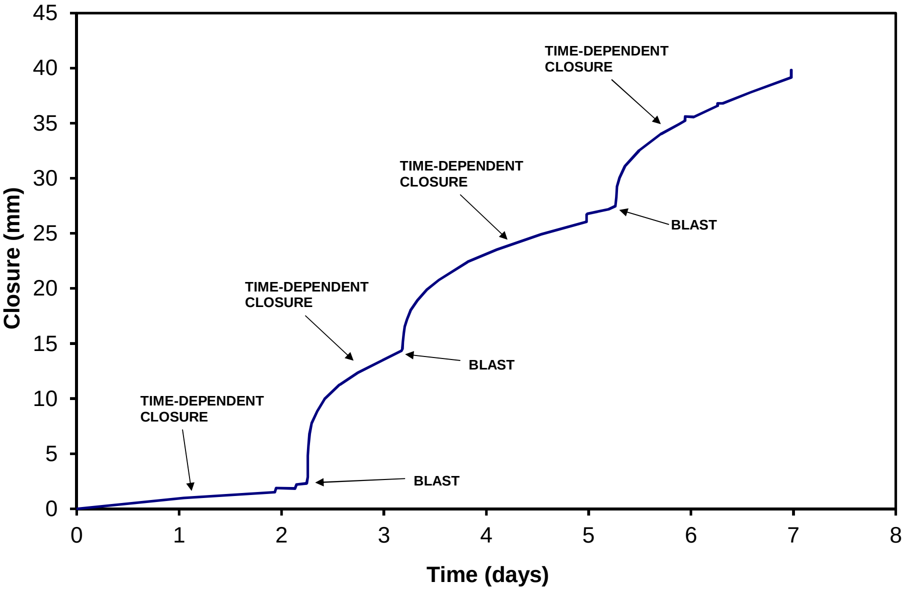

Figure 8. Typical convergence data recorded in deep gold mines and some of the deeper platinum mines where crush pillars are used. This particular data set was recorded in a Merensky Reef platinum stope (after Malan et al., 2007).

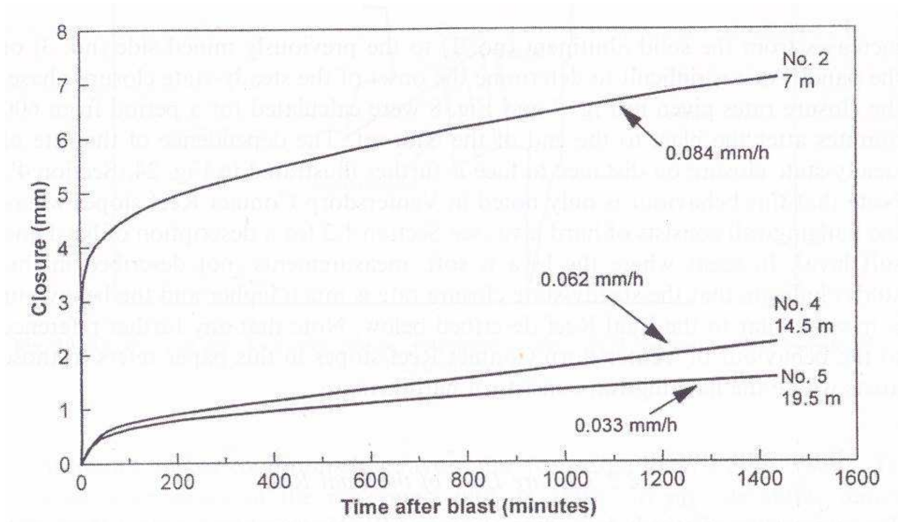

Figure 9. Convergence as a function of time after blasting for different distances to the face. The distance below each meter number is the distance to face before this particular blast (after Malan, 1999). This was recorded in a deep gold mine.

A PROPOSED TIME-DEPENDENT LIMIT EQUILIBRIUM MODEL

As an alternative to the viscoelastic model, a time-dependent limit equilibrium model built into the displacement discontinuity code, TEXAN, was recently used to investigate the convergence behaviour described above. A description of the TEXAN code and the limit equilibrium model is given in Napier and Malan (2012, 2014). By using this approach, the fracture zone surrounding the excavations is simplified as the model restricts failure to the on-reef plane only. A key feature of the model is that the intact rock strength is differentiated from the residual strength according to specified intact and residual failure strength envelopes. The strength of the intact seam or reef material ahead of the stope face is assumed to be defined by a linear relationship of the form

$$\sigma_n = \sigma_c^i + m_i \sigma_s \,, \tag{1}$$

where σ_c^i and m_i are the intercept and slope parameters respectively. σ_s is the average seam-parallel confining stress and σ_n is the seam-normal stress component. Once a point in the seam fails, the strength parameters are postulated to decrease immediately to values σ_c^0 and m_0 which define an initial limit stress state in which there is a fixed limit equilibrium relationship between σ_n and σ_s of the form

$$\sigma_n = \sigma_c^0 + m_0 \sigma_s \tag{2}$$

The limit strength parameters are then assumed to decay towards residual values σ_c^f and m_f . The strength values $\sigma_c(t)$ and $m(t)$ at an elapsed time *t* after failure, are defined according to the relationships:

$$\sigma_c(t) = \left(\frac{1}{2}\right)^{\frac{t}{\lambda}} [\sigma_c^0 - \sigma_c^f] + \sigma_c^f \tag{3}$$

$$m(t) = \left(\frac{1}{2}\right)^{\frac{t}{\lambda}} [m_0 - m_f] + m_f \,, \tag{4}$$

where λ is a half-life parameter. The limit stress components σ_n and σ_s at a given seam or reef position and time *t* are then given by an appropriate equation of similar form to equation [1]:

$$\sigma_n = \sigma_c(t) + m(t)\sigma_s \,. \tag{5}$$

The distribution of the limit stress values will in general depend on the distribution of failure times at all points in the fractured material and consequently depends in a complex evolutionary manner on the planned mining sequence and extraction rate. A given mining problem must therefore be solved in a series of time steps which include mining increments that are scheduled at appropriate time step intervals. The problem time scale will be determined essentially by the chosen half-life parameter, λ .

SIMULATION OF TIME-DEPENDENT CONVERGENCE

The simplified geometry shown in Figure 10 was used to illustrate the characteristics of the time-dependent limit equilibrium model. This is a stope of size 100 m × 50 m situated at a depth of 2000 m. The stope is surrounded by a region of elements which assume the constitutive behaviour described by equation [3] to [5] once failure is initiated. Convergence profiles were recorded at the points A, B and C. These measurement positions varied slightly depending on the element sizes used, but for 1 m elements, the distances to the excavation face were A = 0.5 m, B = 4.5 m and C = 24.5 m. The model parameters are given in Table 1. These parameter values are assumed and needs to be calibrated in future.

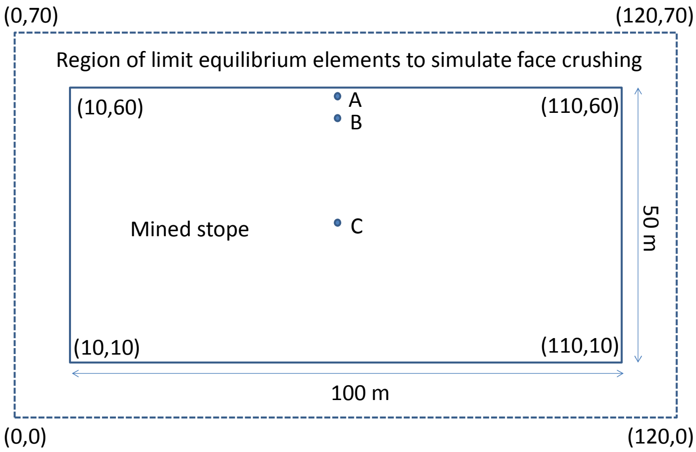

Figure 10. Geometry simulated.

Table 1. Parameters used for the initial simulations.

Parameter	Value
Depth	2000 m
Mining height	3 m
Young's modulus	70 GPa
Poisson's ratio	0.2
Intact seam strength	40 MPa
Intact seam slope parameter	7
Initial crush strength	40 MPa
Initial crush slope parameter	4
Residual strength	1
Residual slope parameter	2
Interface friction angle	20°
Seam stiffness modulus	80000 MPa/m
Half-life	20 h

The simulation attempted to replicate the underground convergence behaviour shown in Figure 9. The simulated results are shown in Figure 11 and the time-dependent nature of the convergence is clearly visible. The rate of time-dependent convergence decreases into the back area of the stope similar to the underground observations (Malan and Napier, 2017). This model is therefore clearly an improvement on a simple elastic model and the viscoelastic approach which could not replicate this behaviour. Figure 12 illustrates the failed limit equilibrium elements (red) and the intact elements (green).

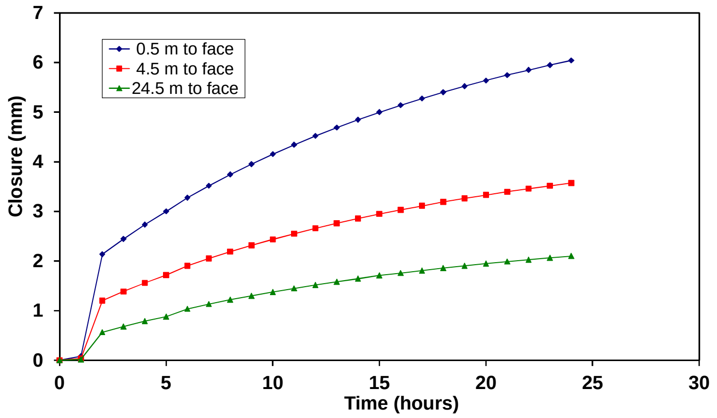

Figure 11. Simulated time-dependent convergence at various distances to face. This only shows the time dependent convergence and not the initial elastic convergence.

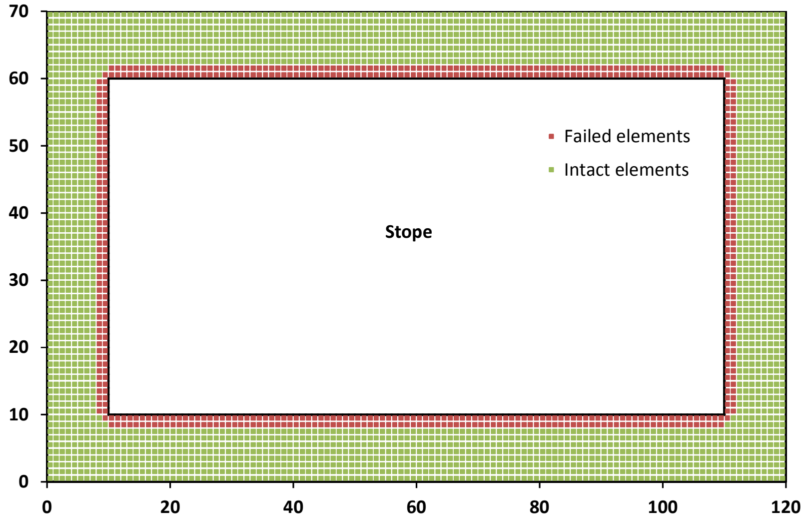

Figure 12. Failed elements (red) at the edge of the stope for the simulation in Figure 10 at t = 24 hours. The intact elements are shown in green.

Based on this intial success to simulate the time-dependent behaviour recorded in deep tabular stopes, this model is currently being investigated further. Preliminary results not described here indicate that the model appears useful to simulate practical mining problems such as the effect of mining rate (Napier and Malan, 2014) and the behaviour of crush pillars in intermediate depth platinum mines (Du Plessis et al, 2011). It is therefore a major improvement when compared to the original elastic tabular simulation tools. A major challenge remaining is calibration of all the parameters shown in Table 1 for site-specific conditions.

SUMMARY

Systematic rock mechanics research to understand the rock burst problem in the South African gold mines was only initiated in the early 1960's. The first major breakthrough was the understanding that the far-field rock mass behaviour can be approximated by elastic theory. This led to the development of a number of simulation tools to determine the stresses and displacement around these tabular excavations. The MINSIM-type codes became very popular in South Africa is it could efficiently solve irregularly shaped tabular excavations on a mine-wide scale. A major drawback of these elastic codes was that it could not solve phenomena associated with the extensive fracture envelope surrounding the excavations. One example is the effect of mining rate as the “creep-like” behaviour of the fracture zone and associated time-dependent convergence cannot be simulated using an elastic approach.

Earlier work indicated that a viscoelastic model is not suitable to replicate the spatial behaviour of the convergence recorded underground. A time-dependent limit equilibrium model implemented in the TEXAN code appears to be a useful alternative as it can explicitly simulate the on-reef time-dependent failure of the reef seam. A key finding of recent studies is that the model gives a good qualitative agreement with the underground measurements. For both the model and actual data, the rate of time-dependent convergence decreases into the back area. It appears that such a model, where the failure is restricted to the reef plane, will provide significantly enhanced modelling capabilities to rock engineers without sacrificing too much of the inherent simplicity of an elastic tabular solver. Calibration of the constitutive failure model nevertheless remains a significant challenge.

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