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Preliminary evaluation of the proposed mining method at Eland Platinum Mine

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This paper describes the preliminary evaluation of the proposed underground layout at Eland Platinum Mine. It is planned to introduce a mechanized mining method at the mine.A complicating factor is the relatively steep dip of the ore body at 18° and the proposed bord and pillar layout therefore utilizes drives on apparent dip. The pillars are staggered and it is planned to support the holings using grout pack ribs. Strike roadway pillars will be used to isolate the different levels. A key question that had to be addressed is to what extent the shear zone in the hangingwall will affect the stability of the pillars; numerical modelling was conducted to investigate this problem.The only practical method to solve tabular layouts on a minewide scale is to use a displacement discontinuity (DD) approach. The traditional DD modelling tools of the South African mining industry were mainly used to investigate problems associated with the deep gold mines. For these problems, it is generally adequate to use a so-called 'infinite' depth assumption. This approach is not suitable for the analysis of shallow-depth platinum mining problems. The TEXAN code was therefore used to evaluate the proposed layout at Eland Mine as it was specifically designed to solve mining layout problems in the Bushveld Complex. The paper describes the numerical simulations in detail and illustrates the simulated pillar stresses and the height of the tensile zone in the panels. These results are used for a preliminary evaluation of the expected stability of the excavations

Introduction

Eland Platinum Mine is situated on the extreme eastern edge of the western limb of the Bushveld Complex (Figure 1).The UG2 Reef, with three distinct facies in this area, namely the Normal, Split Reef and Zilkaatsnek, dips at between 18° and 30° degrees in a northern direction and the reef widths vary between 1 m and 24 m. The Merensky Reef has a similar dip and dip direction to that of the UG2 Reef, but as its values are evenly disseminated over the full 10 m of the thickened pyroxenite, the Merensky Reef is considered to be uneconomic and is therefore not mined.

Owing to the geotechnical complexity of the ground in this area, the mining conditions are extremely challenging when compared to many of the other platinum mines in South Africa. Mining is complicated by the presence of well developed clay-filled shear zones and ramp structures in the hangingwall. The most prominent hangingwall shear at Eland Mine is sometimes referred to as the 'mud layer' owing to the thick clay-like gouge infilling.

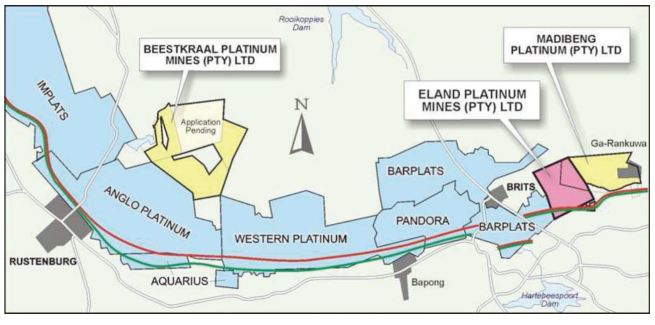


Figure 1. Location of Eland Platinum Mine

Eland Platinum Mine is currently mining three different operations, namely the open pit, Kukama Shaft and Nyala Shaft. The open pit is exploiting the UG2 reef at a depth of between 45 m and 80 m for the full strike length of the property. This opencast mining will be completed in late 2011 and backfilling will be completed the following year. A thirty-metre crown pillar has been left below the open pit to isolate the underground workings and to limit water inflow. The two shafts are being developed from the bottom of the open pit and the current underground operations are planned to a depth of 1 300 m. Thereafter, vertical shafts are planned to allow for mining to greater depths.

The Eland mining method

During the preliminary mine design process the following key driving factors were identified:

- The steep dip will increase dilution.
- The presence of the hangingwall shear will pose a significant risk to both men and material as the stability of the spans between the pillars will be negatively affected.
- The presence of the hangingwall shear might affect the strength of the pillars and therefore affect the extraction ratio negatively.

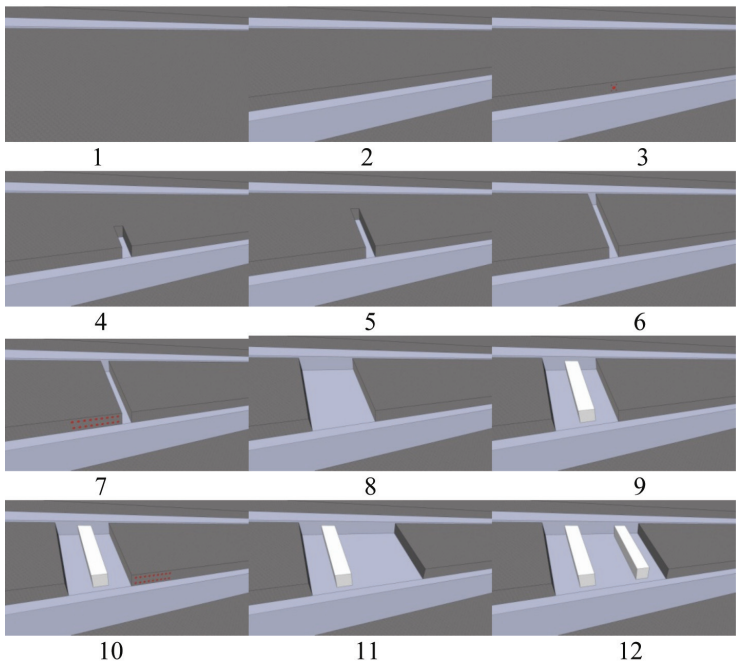


Figure 2. Planned sequence of the Eland Mining Method

- A flexible mechanized mining method needs to be employed if high volumes of ore need to be extracted.

Mining on apparent dip increases the amount of development required to access new ore reserves. A compromise must therefore be struck between the best angle for the mechanized equipment and the angle required to access ore reserves at the required speed.At Eland Mine, this compromise has resulted in the shafts and drives being developed at an apparent dip of 9° and with additional waste being mined from the footwall to allow machinery to travel easily.

Long-hole drilling was identified as a possible method to limit dilution within the holings between pillars. Long hole drilling has been tried on a number of mines in the Bushveld with limited success. The reasons for failure have been identified as rolling reef, handling of misfires, the difficulty of cleaning long flat panels (20 m to 30 m long panels with dips of less than 9°), drilling accuracy and speed, as well as the supporting of large spans created by the large blasts. At Eland Mine two panel lengths are being tested, namely 6 m and 9 m at a dip of 18°. The holings are a maximum of 12 m wide and are being blasted and supported in two cuts. The drilling is being done with specially modified drilling equipment which combines the drilling abilities of the Solo7 drill with the LP chaise. Additional electronic packages have also been added to increase drill accuracy. Each cut is supported using a specially designed grout pack that can be installed from the drive without the need to enter the panel. Cleaning is done using remote operated dozers. If for any reason it is required to enter into a panel, the distance travelled in panel will be minimal and the installation of support for temporary access will not be onerous. The planned mining sequence is shown in Figure 2.

The ubiquitous nature of the hangingwall shear zones, as well as the associated ramp features, will result in very poor ground conditions at Eland Platinum Mine. In these poor ground conditions, the stability of the inter-pillar spans will be problematic. In an attempt to squeeze the maximum

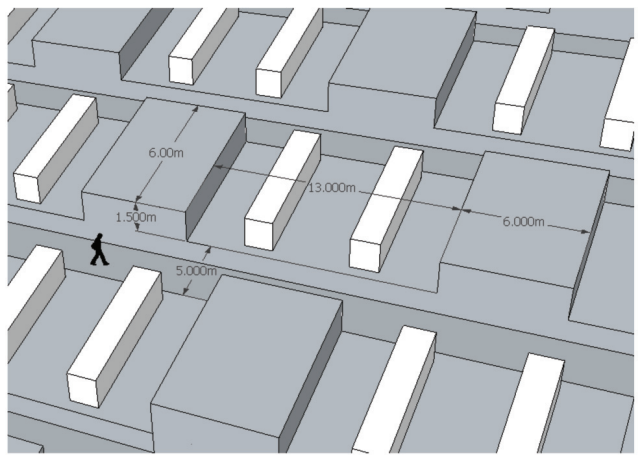


Figure 3. Planned layout of the Eland mining method

panel lengths out of the maximum calculated stable spans, it is planned to offset the pillars as shown in Figure 3. The planned macro layout is shown in Figure 4.

The grout pack ribs at Eland Mine are required to run the full length of the panel; they should be installed remotely and be able to carry the full weight of the maximum estimated fallout height. As the packs need to be installed remotely, the installation process of the structural support, which is traditionally timber elongates, becomes a problem. Although the installed bag can be secured using straps to prevent slide and yaw, roll and pitch are far more difficult to control. These two problems have been addressed using designs developed in conjunction with the bag supplier. The bag will be rolled out into the stope using compressed air or water and will be secured to pigtail eyebolts installed in the footwall of the top drive. Figure 5 illustrates the method to secure the bag. The grout is to be a mixture of clasified UG2 tailings fly ash and cement.The design requires a strength of 4 MPa after 28 days. If the packs are blasted

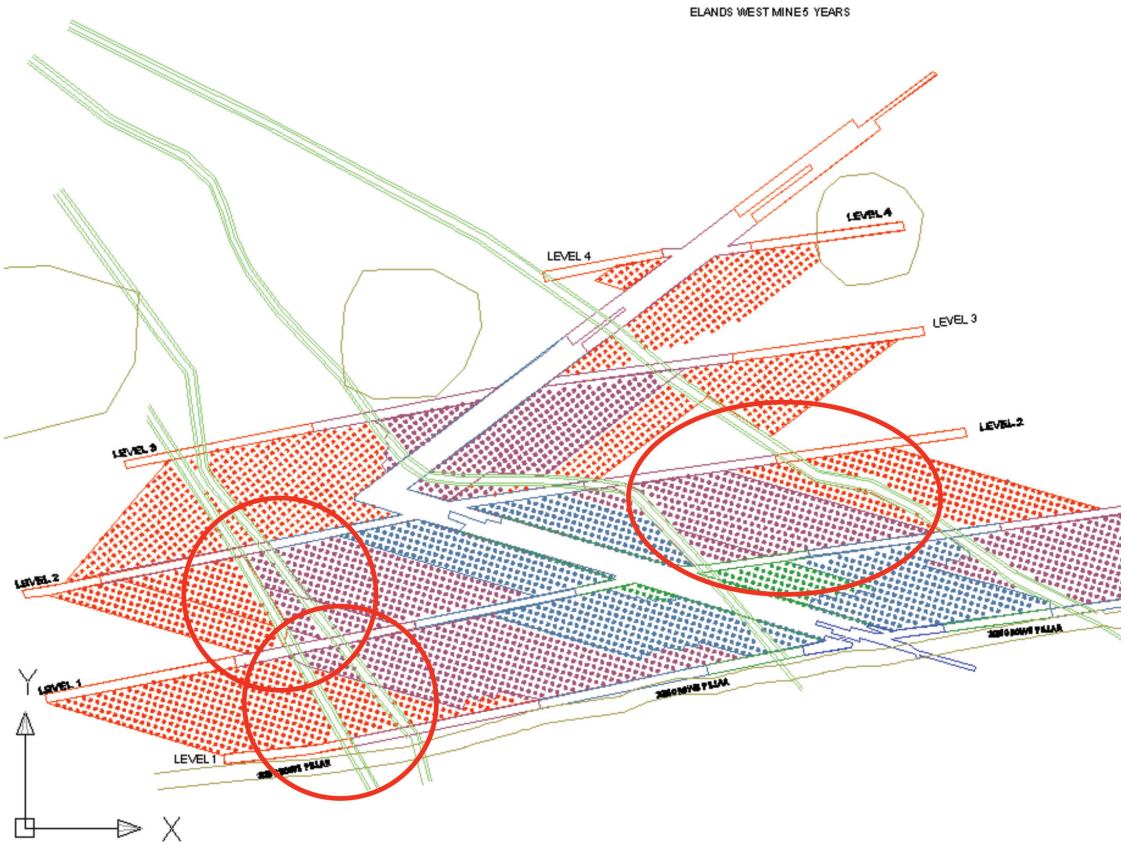


Figure 4. The planned macro layout at Eland Platinum Mine

Figure 5. Design and anchoring of the grout pack ribs to be used at Eland Platinum Mine

onto, this strength will be increased accordingly. The bags are designed to weep and the bottom layer will be dry before the second layer is full. This will reduce shringkage and when combined with the 18° dip, should provide good hangingwall contact.

Numerical modelling of the planned layout

Numerical modelling approach and geometry simulated

The only practical method to solve tabular layouts on a minewide scale is to use a displacement discontinuity (DD) approach. The traditional DD modelling tools used in the South African mining industry were directed mainly to problems associated with the deep gold mines. In these cases, it is generally adequate to use a so-called 'infinite' depth assumption. This is inadequate for the analysis of shallow-depth platinum mining problems. In addition, it is often important in these cases to assess tensile stress distributions near excavation surfaces. Constant strength DDs, as used in the traditional codes, cannot simulate these tensile stresses accurately. The TEXAN code was therefore used to evaluate the proposed layout at Eland Platinum Mine as it was specifically designed to solve mining layout problems in the Bushveld Complex. It addresses the shortcomings of the traditional codes by including fully analytic half-space influence functions and by allowing higher order element displacement discontinuity shape functions to be used. In addition, element shapes may be assigned as triangles or quadrilaterals to facilitate the representation of irregular pillar layout geometries. Detailed descriptions of the TEXAN code are given in Malan and Napier (2006) and Napier and Malan (2007) and the reader is referred to these documents for additional information.

The first objective of the numerical modelling study was to obtain improved estimates of average pillar stresses in the mined areas. Tributary area theory does not take the effect of the strike roadway pillars or abutments into account and therefore overestimates pillar stresses.A further important parameter to simulate is the expected stresses on the strike roadway pillars.

Regarding the geometry simulated, if the drives are developed on apparent dip, it is expected that this inverted 'Christmas tree' shape will eventually be mined, as is shown in Figure 6 (also see Figure 4).

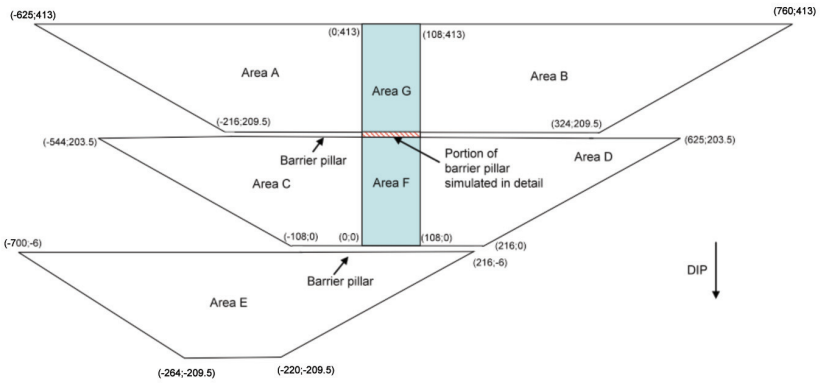


Figure 6. Geometry simulated with the TEXAN code

The simulated APS values are dependent on the element sizes used, and very small elements need to be used to accurately simulate these values. As the total mining area shown in Figure 6 is 446 109.5 m^2, it would be impossible to simulate this entire area in detail with small element sizes (e.g. 1 m^2 elements). To overcome this problem, only areas F and G and the portion of the strike roadway pillar between these areas were simulated in detail and the surrounding area was approximated using equivalent stiffness elements.

For the purposes of this study it was assumed that the area to be simulated in detail could be considered to represent the unit cell. The overall layout solution is determined by solving a problem with the detailed area of interest represented exactly, but with the surrounding mined region represented by a 'few' large blocks of mined ground in which the detailed mining pattern is replaced by a single 'seam' material having a suitable equivalent linear stiffness modulus. The equivalent stiffness modulus was determined by performing a sequence of simple layout analyses as follows.

- The exact layout configuration of one of the detailed areas of interest (Area G) was solved with no surrounding mined areas.
- The average elastic convergence in the solved area of interest was determined.
- The mining layout in Area G was replaced with a number of 'coarse' elements that cover the same overall area.
- The coarse representation of the area of interest was solved using a range of values of stiffness modulus, as the constitutive parameter in each coarse element.
- By interpolation, the equivalent stiffness modulus which yields the same average elastic convergence as determined in the detailed solution of the area of interest in step 1, was determined. This value was found to be ≈2 260 MPa/m.
- Finally, the overall layout comprising both the detailed area of interest and an appropriate number of 'equivalent stiffness' elements that cover the entire layout extent was solved.

Simulated pillar stresses

The pillar stresses in Area F and G (see Figure 6) were simulated. Figure 7 illustrates the stresses in Area G and F for increasing pillar depth. The pillar stresses according to tributary area theory (TAT) were also calculated and plotted in Figure 7. Note that the simulated stresses underestimate the TAT values if the effect of the far field mining is excluded. It does match the values very well, however, if the effect of the far field mining is simulated using the equivalent stiffness elements. TAT cannot take the effect of the up-dip abutment or the strike roadway pillar into account, but the modelling correctly shows that the stresses on the pillars close to the edges is lower than that predicted by TAT. The modelling nevertheless indicated that TAT is a very good approximation for pillars further than 2 rows away from the abutments or the strike roadway pillars.

The good agreement between TAT and the simulated pillar stresses provides the confidence to use the modelling to simulate the stresses on the strike roadway pillars (these cannot be calculated using TAT). The simulated strike roadway pillar stresses between the first and second levels (134 m depth) and the second and third levels (195 m depth) is shown in Figure 8. The values of 13.3 MPa and 15.8 MPa are relatively low. These pillars were originally not planned strictly as barrier pillars, but for other purposes such as ventilation control. These strike roadway pillars should nevertheless be squat to give them the necessary long-term strength and should be probably be cut with a width to height ratio of not less than 10:1 (Jager and Ryder, 1999). For the 1.8 m pillar height at Eland Mine, this implies a pillar width of 18 m (3 times the current planned width). Some consideration is currently given to increase the size of the strike roadway pillars, especially in light of the relatively weak pillar strength expected for Eland Mine. The spacing between these pillars also exceeds the accepted norm of not more than half the mining depth. Work is currently being conducted to revise the layout to include a systematic pattern of barrier pillars.

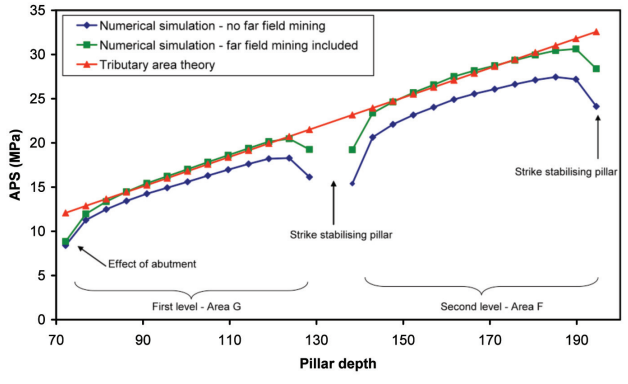


Figure 7. Simulated pillar stresses in Areas G and F

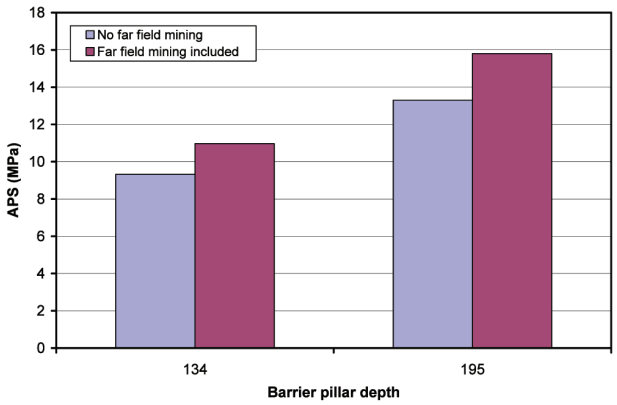


Figure 8. Simulated APS values for the strike roadway pillars

Numerical simulation of the height of the tensile zone in the panels

Some analytical solutions are available to calculate the height of the tensile zone (of some use for support design) in the hangingwall of the panels. The solutions assume an infinite depth and it is not clear what error is made when using these equations at shallow depth. The actual geometry is also more complex than the simple geometries assumed for the analytical solutions. Modelling was therefore conducted using the TEXAN code to obtain an accurate solution of the height of the tensile zone in the intersections of the planned layout at Eland Mine. Prior to simulating the complex geometries, comparisons (not shown in this paper owing to space limitations) were made between the numerical modeling results and the analytical solutions to ensure that the code can accurately simulate the height of this tensile zone. The results were very satisfactory and this gave the necessary confidence in the code for simulating the more complex 3D geometries.

To simulate the height of the tensile zone close to the excavation surface, higher order elements had to be used and to limit the computer run times, the size of the model was therefore restricted to a size of 80 m × 104 m. Higher order (9 collocation points per element) square elements of 1 m size was used. The total number of elements was 8 321, giving a total number of collocation points of 74 889. The layout simulated is shown in Figure 9. Although the actual dip is approximately 18°, for the simulations of the height of the tensile zone, the excavation was simulated with no dip at a depth of 70 m to simplify the positioning of the hangingwall benchmarks. Figure 10 illustrates the simulated vertical tensile stress in the hangingwall for the various benchmark positions. The height of the tensile zone is greatest in the centre of the holing and has a value of 1.7 m at this position.

Numerical simulation of the excess shear stress in the hangingwall

To investigate the propensity for slip on the shear plane in the hangingwall, the excess shear stress (ESS) values were calculated on planes parallel to the reef at various distances into the hangingwall (1 m, 2 m and 5 m) for Region G in Figure 6. The grid of benchmark points was located in an area covering part of Area G and only the upper part of Area F. The results for a friction angle of 10° (the friction angle is expected to be very low for the shear zone) are shown in Figure 11. At a distance of 1 m into the hangingwall, there are prominent areas of large positive ESS (indicating slip) surrounding the pillars. This propensity for slip becomes less as the distance into the hangingwall increases. Of interest is that if the friction angle is increased to 32°, this propensity for slip disappears for the plane at 5 m height. For the plane at 2 m height, the friction angle, however, needs to be increased to an unrealistic 80° to prevent slip. These results indicate that hangingwall stability will be a problem at Eland Mine owing to the steep dip and the presence of the shear zone.

Effect of the shear zone on pillar strength

Of significant concern at Eland Mine is that the weak layer in the hangingwall may significantly affect pillar strength and some work was conducted to investigate this possibility. A large number of publications on pillar strength are available and the reader is referred to these publications for the required background information. Some of these references are Salamon and Munro (1967), Bieniawski (1992), and Watson *et al*. (2008). Other workers have shown that that a weak interface between the hangingwall and pillars may reduce pillar strength significantly (Wagner (1980) and Peng (1978)).

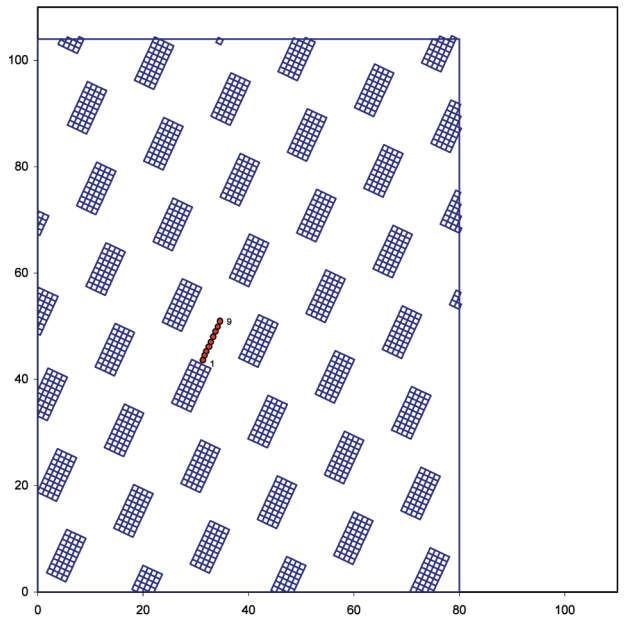


Figure 9. Size of the geometry simulated to investigate the height of the tensile zone at a depth of 70 m. The dots indicate the positions where the vertical hangingwall benchmarks were taken

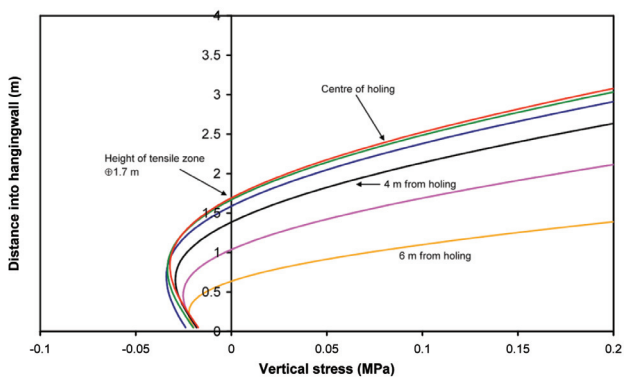
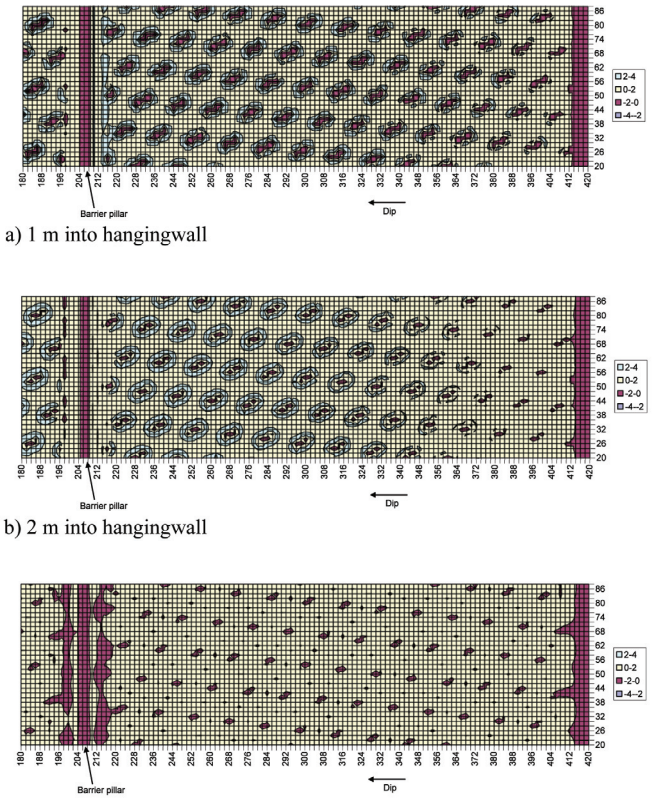


Figure 10. Simulated vertical stress for various positions in the intersection



a) 1 m into hangingwall

b) 2 m into hangingwall

c) 5 m into hangingwall

Figure 11. Simulated ESS values on a plane parallel to the reef. A friction angle of 10° was used for these plots

To investigate this phenomenon at Eland Mine, some additional modelling was conducted for by Dr John Ryder using a finite difference code. The qualitative effect of a strong pyroxonite layer within a chromitite pillar (with weak contacts, including weak hangingwall and footwall contacts) was modelled in 2D. Although the problem at Eland Mine will mainly be one where the shear zone forms a weak contact between the UG2 pillar and hangingwall, a more general model was built to investigate the effect of aninhomogeneous pillar with weak interfaces. Estimated *in situ* strain-softening parameters were drawn directly from the PlatMine 2002 report, Appendix C Table C4. The hangingwall and footwall were assigned the same properties as the pyroxonite layer, and symmetry was assumed for both the vertical and horizontal centrelines in the following layout in the finite difference code (Figure 12). The grid size was 0.1 m × 0.1 m.

By applying slow displacement loading (velocity 5×10^{-4} mm/step), complete stress-strain and lateral deformation curves could be modelled (Figure 13). Lateral deformations showed no dramatic effects due to presence of the 'strong' layer of pyroxonite in the pillar, possibly because the modelled contrasts in strength, Poisson's ratio and dilatancy were not particularly marked. Likewise, the presence of a weak interface between the layer and the body of the pillar had virtually no effect, even if the friction angle of interface 1 was set as low as 6°. In contrast, low friction angles on the hangingwall contact (interface 2) had a powerful effect, reducing the peak strength *p* of the pillar by allowing lateral deformation and reduction of confinement, and reducing also the residual strength (Figure 14).

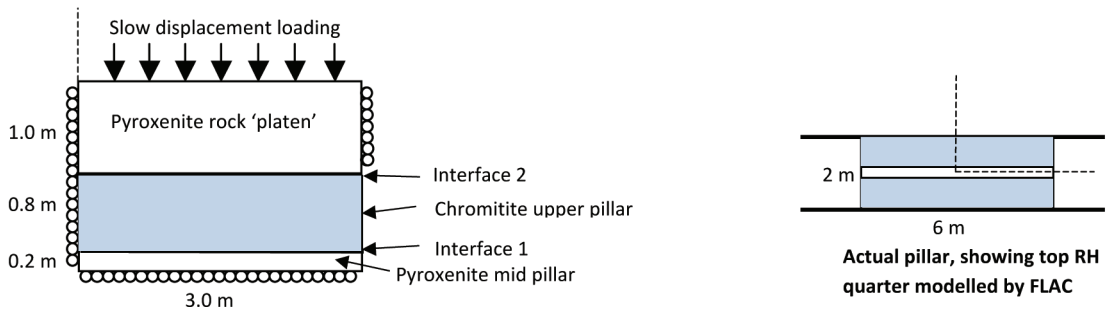


Figure 12. Model geometry of the top right hand quarter of a 2D 6 × 2 m pillar with a central 0.4 m thick pyroxenite layer. Loading is via a confined rock 'platen'

Figure 13. Pillar stress:strain and sidewall dilation (at peak strength point *p*), for interface friction angles of 30°

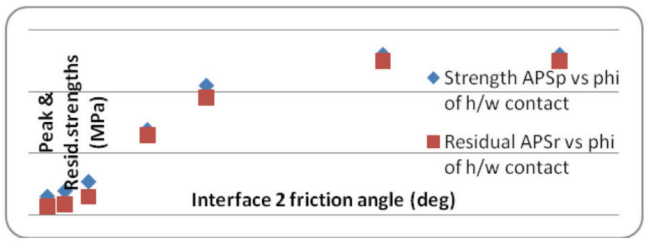


Figure 14. Peak and residual pillar strength versus hangingwall contact friction angle ϕ_2

Additional modelling work was also conducted by Dr Ryder to investigate if the pillars are weakened if the shear zone is located some distance into the hangingwall. A replicated rib layout of 6 m wide pillars on 30 m centres (80 % extraction) was modelled. The mining height was 2 m, so the ribs had a w:h ratio of 3:0. A parting was introduced 1 m up into the hangingwall, but otherwise the pillars and host rock were intact and assumed to possess uniform properties—those of chromitite material as documented in the Platmine 2002 report, Appendix C Table C4. Four-way symmetry was assumed, so that only ¼ of the pillar and surrounds needed to be modelled (though this means that a parting was also present in the footwall). In an initial run with high friction on the parting (89.9°), the pillar reached a peak load (APS) of 560 MPa. In a separate run with friction of only 6° on the parting, the pillar load peaked at only 240 MPa (almost 2.5 times less). Thus the presence of a slippery parting 1 m up into the hangingwall and down in the footwall (owing to the symmetries) appeared to have a considerable weakening effect on the pillar. Closer investigation revealed the mechanism for this: a pillar, especially while its elements are failing, tends to strongly dilate laterally. With normal frictional contacts, both in the laboratory and *in situ*, this dilation is restrained; thus generating lateral confining stresses which strengthen the pillar well above the UCS of its constituent parts. If this confinement is relaxed due to slippery contacts, the peak APS achievable reverts closer to this UCS value (estimated at an *in situ* value of 62 MPa for the chromitite material modelled).

Summary

The TEXAN code was used to simulate the proposed layout at Eland Platinum Mine. Good agreement was obtained between the simulated pillar APS values and the values predicted by tributary area theory. Numerical simulations were also conducted to evaluate the propensity for the shear zone to be mobilized at various heights into the hangingwall. The preliminary results indicate that there is a strong propensity for the shear zone to be mobilized and this will be especially noticeable at the edges of the pillars. As this will affect the stability of the hangingwall, appropriate support measures will have to be implemented to support this unstable ground.

When simulating the proposed layout using higher order elements, it was found that the height of the tensile zone in the centre of the intersections is approximately 1.7 m. The height decreases for positions closer to the pillars. This value of concern as the shear zone might be present at heights less than this. The support of the panels and holings is currently being reviewed and this height of the tensile zone is an important parameter that will be considered.

Regarding a possible reduction in pillar strength owing to the presence of the shear zone, modelling indicated that if a weak shear zone is located at a height of 1 m into the hangingwall, a significant reduction in pillar strength will be experienced. It is therefore prudent that for the classical empirical pillar design methodologies, a significantly downrated pillar strength be used. As a first approximation, for the Hedley and Grant formulation, a *K*-value of 30 MPa or less will have to be used. From the simulated APS values and the first approximation of pillar strength (K = 30 MPa), it appears as if a factor of safety of 1.6 will be maintained for the first two levels at Eland Mine using the existing design. At deeper levels, an alternative design will, however, have to be explored if the assumption of K = 30 MPa is correct.

It should be noted that although the expected stresses on the pillars can be reasonably accurately estimated using the modelling techniques described in this paper; a far more difficult problem is to compute the pillar strengths. Little information is available and no standardized design methodology has been developed for pillars where a slippery interface is present at the pillar hangingwall contact or in the immediate hangingwall. The *K*-value estimated above should therefore be considered as a first order approximation only. A trial mining section is planned for Eland Mine where appropriate instrumentation will be installed to verify the numerical modelling results. Back analysis of this trial mining area and the monitoring results can then be used to verify the pillar strength estimates. In light of the expected weak pillar strength, the layout also needs to be revised to include barrier pillars at appropriate spacings.

Acknowledgements

The authors wish to thank Dr John Napier for his assistance with the numerical modelling study and his ongoing efforts to develop the TEXAN code. Dr John Ryder is thanked for conducting the finite difference modelling.We would also like to thank Mr Rodney O'Riley for allowing this work to be done at Eland Platinum Mine, Mr Cules Kolbe for sharing his knowledge and experience.

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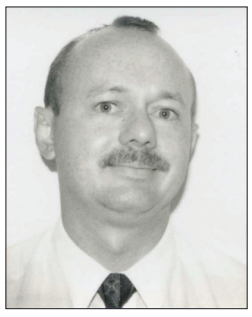
Geoffrey Steven Potgieter is South African, obtained his Chamber of mines Certificate in Rock Engineering in 2006, and is currently studying towards his advanced rock engineering certificate at the University of the Witwatersrand. Having joined Anglo Platinum in 2003, he became Shaft Rock Engineer in 2007. In 2008, he moved to Xstrata Alloys. Geoffrey currently represents the African region on the Young Members' Presidential Group of the ISRM. He is a member of the ISRM, through the South African National Institute of Rock Engineering (SANIRE), having first served as the SANIRE student representative from 2005 to 2009 and then as the SANIRE Communications Portfolio holder from 2009 to date. Geoffrey has worked in conventional and mechanized mining environments both on established mines and more recently on new projects. He is currently part of the multidiscipline team that is bringing Eland Platinum Mine to production. He has gained experience with the reef parallel shearing and associated ramp features which are common in the Bushveld Igneous Complex and which dominate the geotechnical environment at the extreme eastern edge of the western limb of the Complex.



Daniel Francois Malan
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Dr. Malan joined COMRO in 1993 and worked in the fields of numerical modelling and the physics of rock mass behaviour. The work focussed mainly on research into micro-mechanical rock behaviour, the use of boundary element models and laboratory models. During this time, he also gained significant expertise in the time-dependent behaviour of hard rock which he used as a topic to obtain his PhD from Wits in 1998. This won him the ISRM Rocha medal in 2001. Other achievements were to be awarded the Salamon prize in 1997 as well as 15 publications in refereed journals and 22 papers in conference proceedings. After serving for some time as Programme Manager of Rock Engineering at CSIR Miningtek, he joined Groundwork in Feb 2004 as principal consultant and is currently Director of the company. Dr Malan is a registered Professional Engineer with the Engineering Council of South Africa, is a member of the South African Institute of Mining and Metallurgy and is currently serving on the Board of the International Society of Rock Mechanics as a Vice-President. He was also recent appointed as Extraordinary Professor at the University of Pretoria.