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TOWARDS AN IMPROVED PILLAR DESIGN METHODOLOGY AT BATHOPELE MINE

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Abstract

The Hedley and Grant pillar strength formula is widely used within the South African mining industry to calculate pillar strengths in bord and pillar mining layouts, and is currently being used at Bathopele Mine. Bathopele is an operation of Anglo American Platinum near Rustenburg, mining the UG2 reef at depths ranging from 40 m to 300 m below surface. The formula includes a parameter *K*, which is a downrated uniaxial compressive strength value of the rock, used to calculate the strength of a pillar. At Bathopele Mine, for the shallower areas Less than 150 m the value was 33 MPa, but this was increased to 44 MPa due to the fact that rock mass conditions improved and there were no incidence of failure in the shallower areas.
Underground observations showed pillars to be stable with no signs of failure, and it was questioned whether the design was not still too conservative, resulting in sub-optimal extraction ratios and consequently a loss of revenue to the mine. A trial mining section was started at the mine where the pillars were reduced from 6 m x 6 m to 5 m x 5 m and the pillar behaviour was monitored for the onset of failure. Numerical modelling was conducted using the TEXAN code to back-analyse pillar stresses in order to find a more realistic value for *K*. Results from the trial section indicated that the pillar design was in fact too conservative, and the value for *K* was adjusted to 54 MPa for future designs. This paper details the findings from underground monitoring and numerical modelling results, and includes details for further calibration of the *K* value in order to further optimize the extraction of the orebody.

Introduction

Geological setting and locality

Bathopele Mine is a shallow, mechanized bord and pillar platinum mine. It is part of the Rustenburg Platinum Mines lease area, which is situated on the western limb of the Bushveld Complex (Figure 1). The Bushveld Complex is a large layered intrusion occupying a pear-shaped area extending east – west for 480 km across the Mpumalanga, Limpopo, Gauteng, and North West provinces (Lurie, 1977).

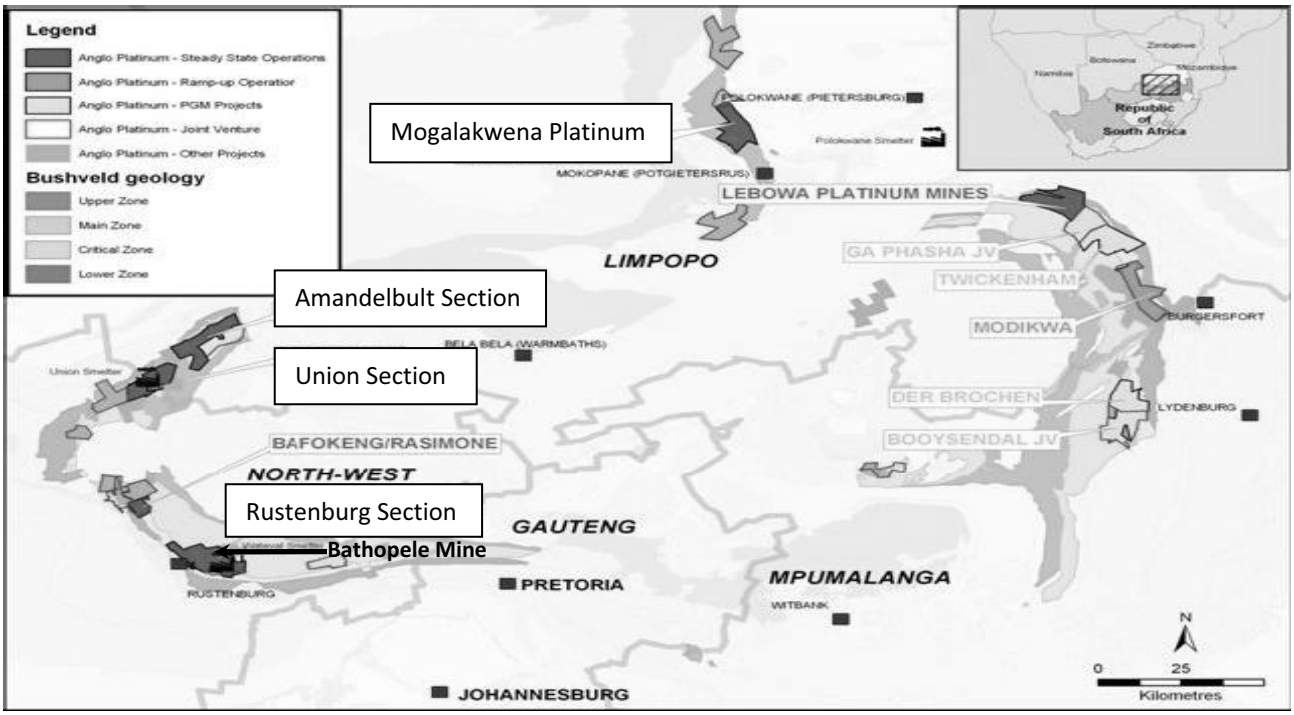

Figure 1-Location of Bathopele Mine and the Bushveld Complex exposure

The platinum group metals are concentrated in two planar orebodies known as the Merensky Reef and UG2 Reef. The middling between the two reefs is approximately 140 m at Bathopele Mine. The reef horizon mined at Bathopele Mine is the UG2. It strikes approximately 55º west of north and has a dip of 9°. The UG2 Reef consists of a chromitite layer which has an average thickness of 70 cm and is commonly underlain by a pegmatoidal feldspathic pyroxenite layer of variable thickness, and less commonly by an anorthosite layer. The UG2 is overlain by medium-grained feldspathic pyroxenite, which hosts a succession of thinner chromitite layers (Figure 2). The mining depth currently ranges from 40 m – 300 m below surface. A sound design for the stability of the mine is essential to avoid hazards such as large backbreaks (stope collapse), surface subsidence, and falls of ground. This is achieved through the use of regularly spaced intact pillars. Little work has been done in the past to determine pillar strength and as a result, pillars have been designed using experience and formulae developed for other hard-rock mines. Such is the case at Bathopele Mine, where the Hedley and Grant formula (derived for Canadian uranium mines) has been adopted to design pillar layouts. Very few pillar failures have been reported in the industry, and it is thought that the value used for *K* yields too conservative a result. This has led to oversized pillars, which lowers the extraction ratio and hence results in a loss of ore.

Pillar history at Bathopele Mine

In order to maintain stability, pillar sizes increase with depth. Pillar sizes are calculated based on stoping widths of 2.0 m and 2.4 m for single-seam and dual-seam mining respectively, using a safety factor of 1.6. Single-seam mining is the term used when the Main Chromitite Seam is mined, and dual-seam mining is when both the Main Seam and the Leader Seam are being mined (Figure 2). Pillar sizes and spans have undergone many changes since the operation commenced, and current panel spans (bord widths) and pillar holings (splits) are 9.0 m. Pillars are designed using the Hedley and Grant pillar strength formula (Equation 1). Originally, K = 33 MPa was used for all depths. Subsequently, K = 33 MPa was used for depths less than 150 m below surface and K = 44 MPa for depths greater than 15 0m below surface. Following the first phase of the pillar reduction trial in July 2010 the K value was increased to 54 MPa, which is probably still somewhat conservative for the pillars at Bathopele Mine, as no pillar failures have been reported.

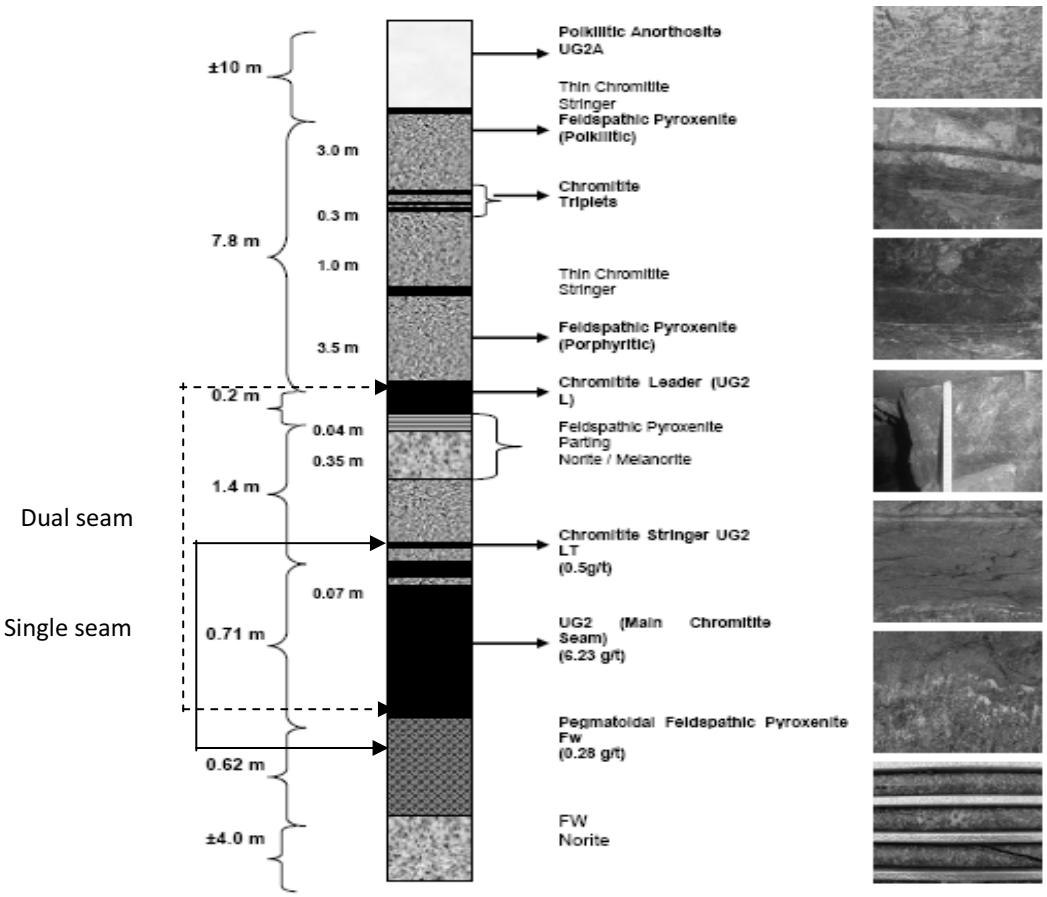

Figure 2-Stratigraphic column indicating single- and dual-seam mining

Hedley and Grant pillar strength formula:

$$\sigma_p = K(w^a / h^b) \quad [1]$$

where σ_p = Pillar strength; *K* = downrated value of uniaxial compressive strength; *w* = pillar width; *h* = pillar height; a = 0.5; b = 0.75.

Methodology used to review the K-value

The experiment was conducted in two phases. Firstly, a trial mining section with reduced pillar sizes was created. An instrumentation and modelling programme was carried out to determine pillar parameters and to show that current design was conservative. Secondly, undersized pillars that were not part of the trial section at Bathopele Mine were back-analysed to determine more realistic *K*-values.

Phase 1 – pillar monitoring of trial section

The original mining layout at the time comprised 9 m bords by 8 m splits with 6 m x 6 m pillars. For the purpose of the trial, the pillars were reduced to 5 m x 5 m and the bords and splits were increased to 10 m, resulting in a factor safety of 1.5 for these pillars. Mining of this new layout commenced in November 2009 and was successfully stopped in July 2010. An area of approximately 24 200m² was mined. The ground conditions were fair (average Rock Mass Rating = 60 per cent). Groundwork Consulting, a consulting company, was requested to execute a monitoring and modelling programme to verify the stability of this area.

As mining progressed, four undersized pillars were selected for detailed monitoring (Figure 3).

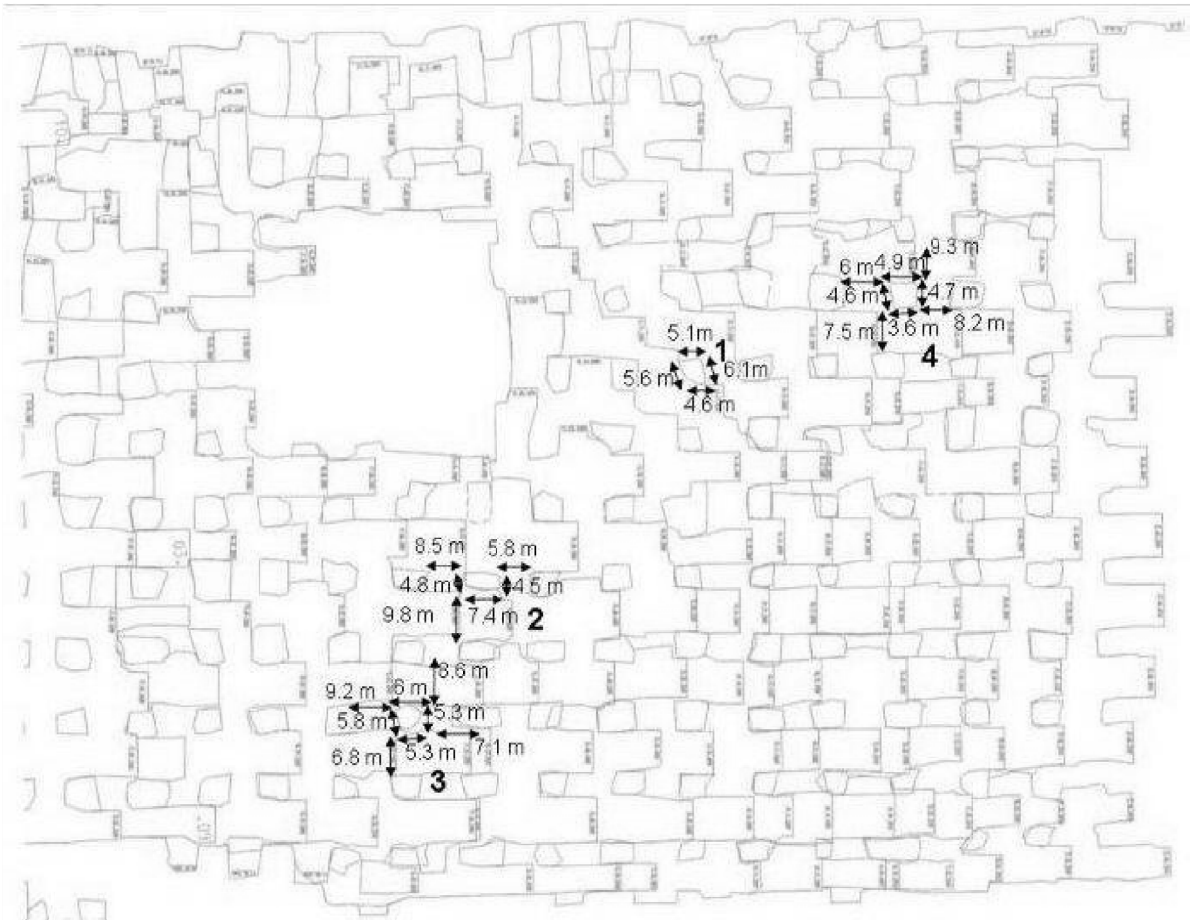

Figure 3-Plan of the trial section showing the position of the undersized pillars that were monitored and their dimensions

These pillars were inspected visually and a photographic record of each side of the four pillars was kept in order to monitor possible deterioration. Figures 4 and 5 show that no time–dependent deterioration occurred for the six month duration of the trial. Borehole camera inspections of the pillar core had not been conducted as no pillar scaling was observed.

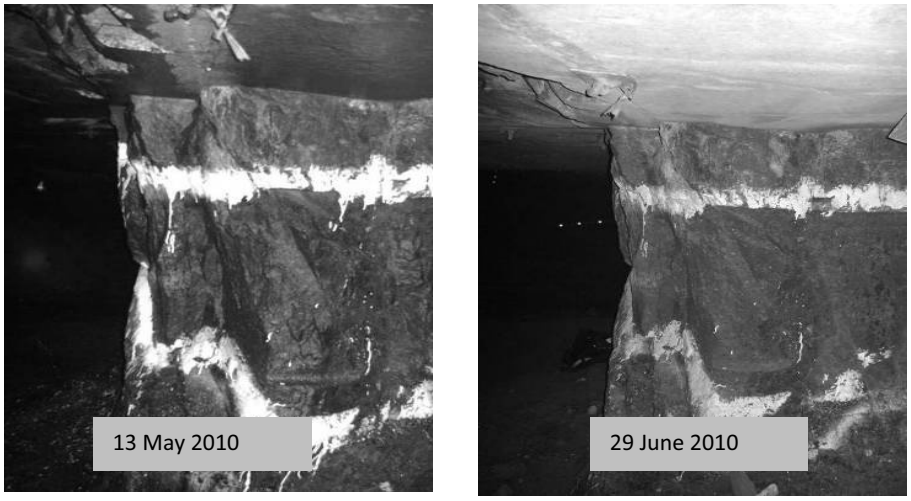

Figure 4-Photographs of the left corner of pillar no. 4 taken on successive dates (after Malan, 2010)

Figure 5-Photographs of the left corner of pillar no. 3 taken on successive dates (after Malan, 2010)

Closure peg stations were installed in the intersections adjacent to each of these pillars to monitor the amount of convergence to supplement the photographic database. A vernier closure meter was used to collect measurements. Table I indicates that the data collected corresponds with the visual inspection and confirms the stability of the trial pillars. Note that a measurement error was made, as a negative value was recorded for pillar 3. This indicates that the stope is 'opening up', which is incorrect.

Table I-Summary of closure measurements

Pillar	Station	Type of measurement	Reading (mm)				Closure (mm)
			13/5/2010	27/5/2010	10/6/2010	29/6/2010	
1	1	Vernier Reading	73	72	73	73	0
		Chain Length		1866			
3	1	Vernier Reading	66	66	66	67	-1
		Chain Length		2064			
	2	Vernier Reading	90	90	90	90	0
		Chain Length		1965			
	3	Vernier Reading	33	33	33	33	0
		Chain Length		2064			
	4	Vernier Reading	52	52	52	52	0
		Chain Length		2163			
4	3	Vernier Reading	-	95	97	95	0
		Chain Length		2064			

A numerical modelling study was done to determine the stresses acting on the pillars in the trial section and to compare the results with the observations made underground. This area was simulated using a displacement discontinuity boundary element program known as the TEXAN code (Napier and Malan, 2008). Average pillar stresses (APS, Equation 2) were simulated and minimum *K*-values were back-calculated for various pillars (Table II). Note that the entry in Table II for pillar 296 will not be used in the analysis, as there was a discrepancy between the size of the pillar measured from the mine plan and the size measured underground. As an example, the underground measured circumference of P296 (pillar no. 3 in Figure 5) was 22.4 m, and not the simulated 18.4 m as indicated on the mine plans. The numerical model was simulated using the mine plan and P296 yielded a relatively high simulated APS value of 63.3 MPa, which is expected to be lower in reality (Malan, 2010).

$$\text{APS} = \frac{q_v}{(1-e)} \qquad [2]$$

where APS = average pillar stress, qv = virgin vertical stress, e = extraction ratio.

Table II-Simulated pillar stresses and back-calculated minimum *K* values for the pillar strength formula

Pillar	Area (m^2)	Mining Height (m)	Equivalent width (m)	APS (MPa)	Minimum *K*-value
124	133.7	2	10.6	26.2	13.5
154	35.7	2	5.8	39.9	27.9
156	45.3	2	6.7	40.6	26.3
158	26.6	2	4.9	51.6	39.1
160	34	2	5.7	48.5	34.1
162	24.2	2	4.9	54.4	41.5
164	27.3	2	5.1	47.8	35.5
166	26.7	2	5.0	51.1	38.5
168	21.7	2	4.6	51.2	40.0
186	138.3	2	11.9	25.8	12.6
261	49.6	2	7.0	40.0	25.4
266	50	2	7.1	45.1	28.5
293	39.8	2	6.3	46.1	30.8
296	20	2	4.3	63.3	51.1
366	36.9	2	6.1	56.4	38.5

Using numerical modelling results, the minimum *K*-values for the pillar strength formulae could now be calculated. Results show that the average minimum *K*-value using the Hedley and Grant formula is 41.5 MPa.

This is considered a somewhat conservative value as the pillars showed no signs of being loaded close to their peak strengths (Malan, 2010). This serves as further evidence that the Hedley and Grant value of *K* = 44 MPa used for design at Bathopele Mine is still conservative.

The first phase of the study was successful in illustrating that the current pillar design is probably conservative. However, uncertainty still existed regarding what an appropriate *K*-value should be.

Phase 2 – back-analysis of other undersized pillars

It was originally planned to carry out Phase 2 of the study in the same trial section where the pillars were reduced from 6 m x 6 m to 5 m x 5 m. The plan was to reduce these pillar sizes further up to the point where failure could be observed. This phase of the study was not started due to a number of major fatal accidents that occurred in bord and pillar operations in the platinum mining industry.

As an alternative to Phase 2 of the trial, it was proposed that other undersized pillars at Bathopele Mine be back-analysed to determine more realistic K-values and to investigate the applicability of the strength formula (Malan, 2010).

Database description

Mine plans were scrutinised to see if significantly undersized pillars could be found, and six areas were identified where back–analysis could be done. Modelling for only four of the six sections was completed for this paper.

The database consisted of 22 pillars, of which one is classed as stable, 9 are unstable, and 12 are classed as failed. Pillars with a factor of safety (FOS) less than 1 should have failed, those with a FOS > 1.6 should be stable, and those within the region between 1 and 1.6 should be unstable. This indicates that they are prone to scaling but have not yet failed. Underground investigation showed that the condition of the undersized pillars was in fact very good, and there were no obvious signs of deterioration. This supported the assumption that the *K*-value was still too conservative, as pillars with factors of safety of 1 or less should have failed (Figure 6).

Figure 6-Photograph of one of the 'failed' pillars still exhibiting stable conditions

The database has a wide range of pillar widths (Figure 7) but the heights ranged between 2 m and 2.4 m (Figure 8). Figure 9 indicates that the width / height ratio of the majority of pillar is 2.

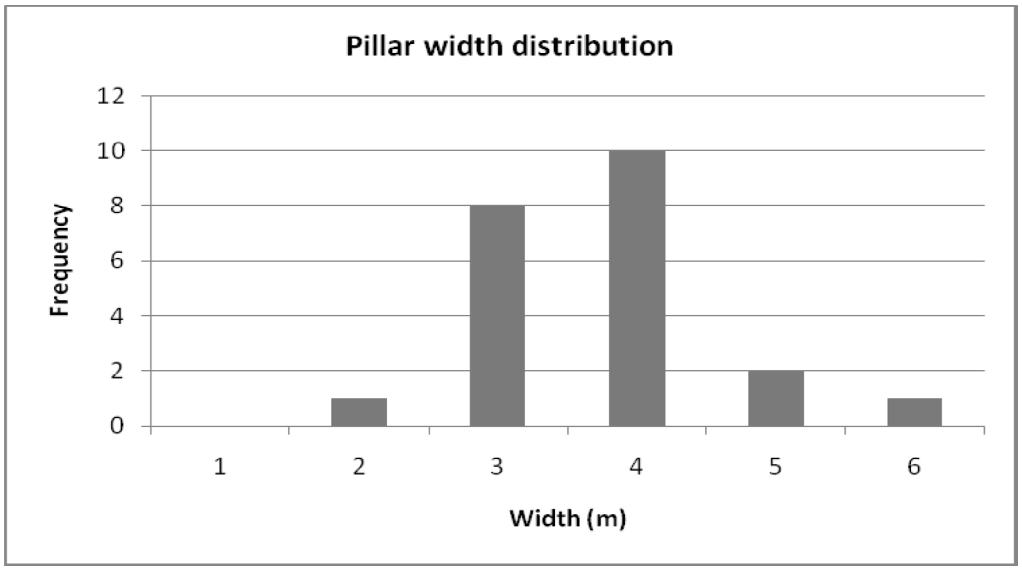

Figure 7-Distribution of pillar widths

Figure 8-Distribution of pillar heights

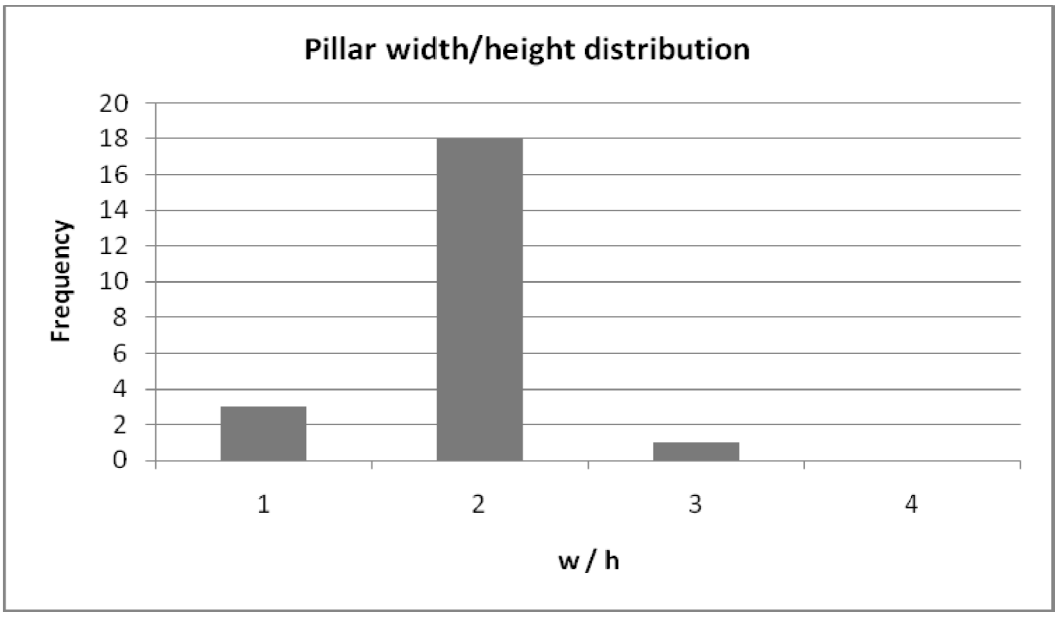

Figure 9-Distribution of pillar width / height ratios

BESOL modelling and analysis

BESOL is a boundary element (displacement discontinuity) program that was used to model the four areas of interest mentioned above.

Each area was modelled separately and a plot of the APS was generated (Figure 10). The depth below surface of the modelled areas ranged between 143 m and 211 m. A *K*-ratio (ratio of horizontal stress to vertical stress) of 1.5 was used, and other modelling parameters can be seen in Table III.

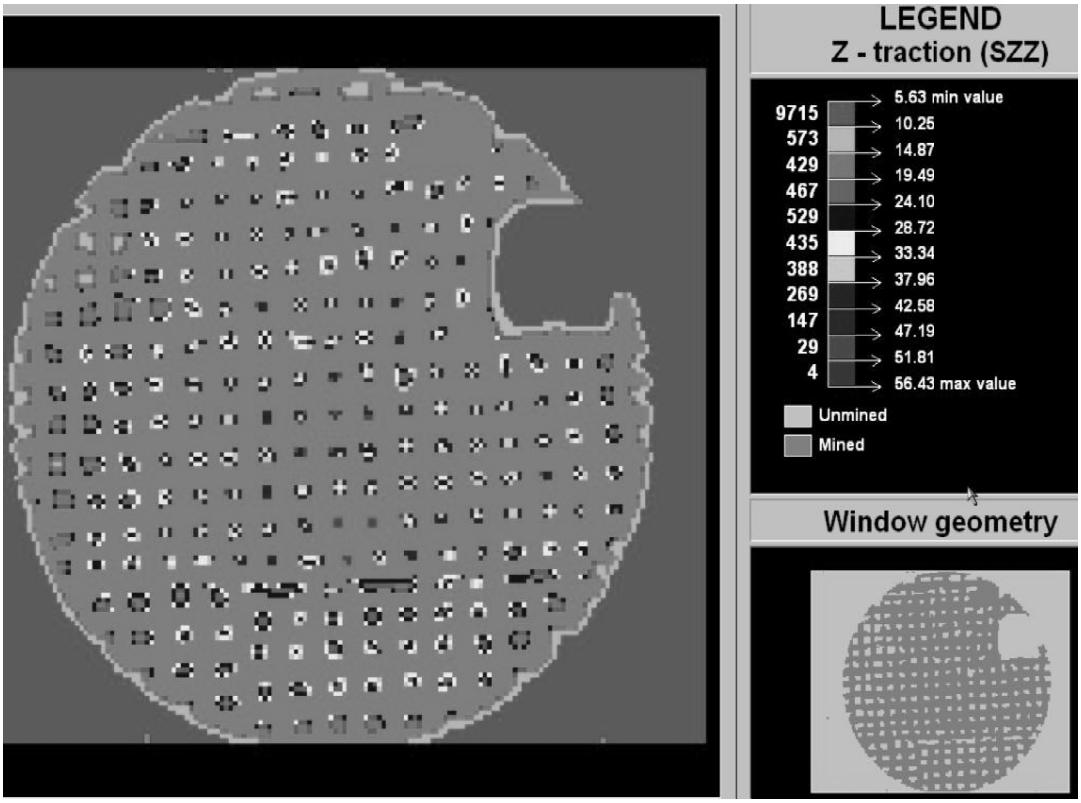

Figure 10-Stress plot of a simulated section

Table III-Parameters used in the BESOL models (after Bathopele Mine COPCRRA, 2012)

Rock Type	Young's Modulus (GPa)	Poisson's Ratio	UCS (MPa)
Pyroxenite	80	0.28	140
UG2 reef	60	0.25	70

From Figure 11 it can already be seen that the modelled APS values are significantly lower than the calculated values using Equation 2.

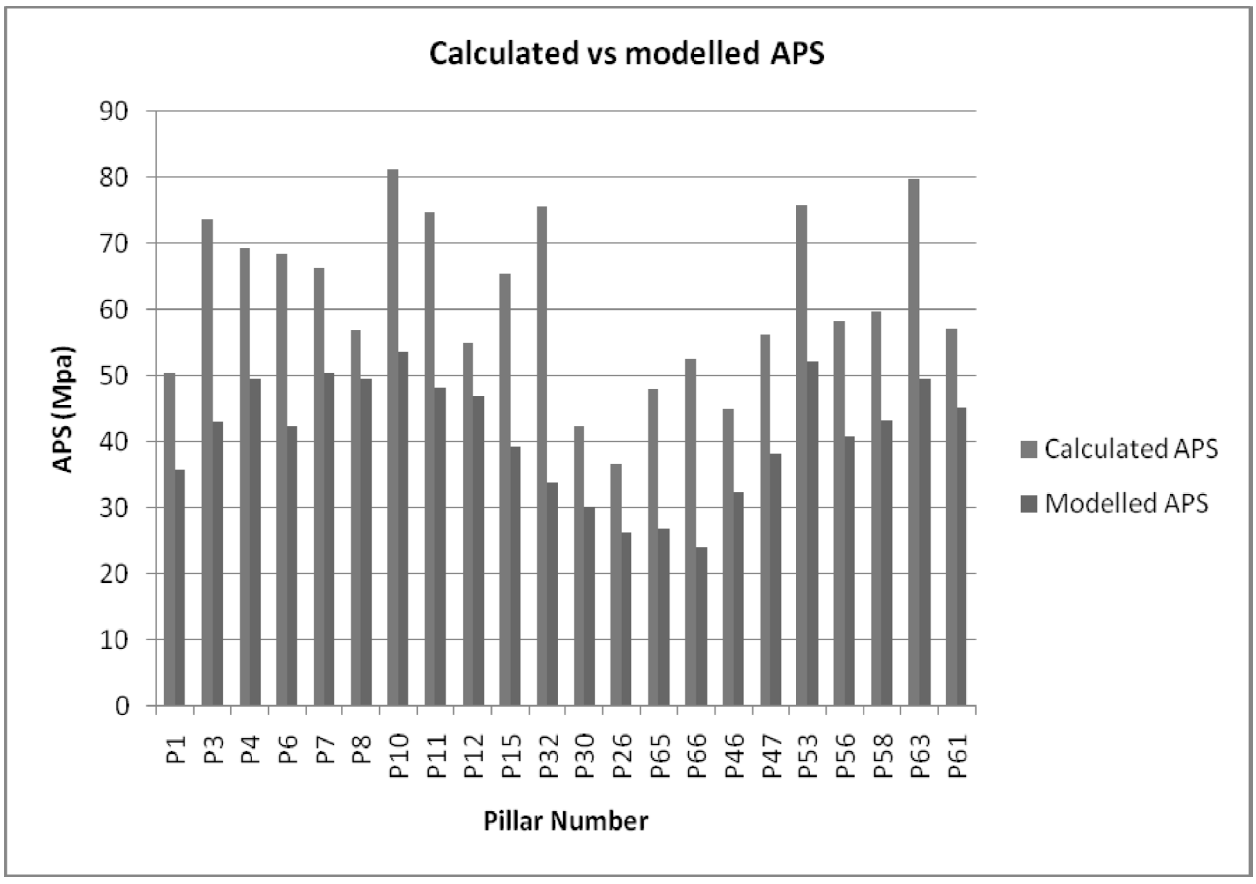

Figure 11-Comparison between calculated and simulated pillar stresses

Back-analysis of the *K*-value was not completed as the remaining two sections of undersized pillars have to be modelled.

Conclusion and recommendations

The first phase of this experiment was successful in proving that the K-value used in design was too conservative. Following this trial, the *K*-value was increased from 44 MPa to 54 MPa. This resulted in a 2.6 per cent overall increase in extraction ratio. During 2011 an additional 99 ounces of refined platinum was gained at an estimated revenue of R1.85 million. The projected additional refined platinum ounces that may be obtained between 2012 and 2014 is 4802 ounces, with an estimated revenue of R89.8 million. This provided the motivation for the commencement of the second phase. The second phase has not yet been completed but the progress to date shows that the new *K*-value of 54 MPa may still not be appropriate.

Research done by Malan (2010) and Watson (2010) used a database of 178 and 179 pillars, respectively. Hence, Bathopele's database needs to be expanded to produce more technically sound results.

Firstly, the second phase of the experiment must be completed. A back-analysis of 'undersized' pillars must be conducted in order to determine a more realistic *K*-value to use in design.

A section with pillars already being mined with *K* = 54MPa should be used as a trial section where certain pillars can be further reduced in size. This would allow for a meaningful back-analysis of the *K*-value and pillar strength parameters, which will ultimately result in an optimal extraction ratio. It is believed that there is potential to achieve *K*-values within the regions of 70 – 80 MPa.

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