The determination of the residual strength of hard rock crush pillars with a width-to-height ratio of 2:1

by D.P. Roberts*, M.K.C. Roberts*, A.J. Jager*, and S. Coetzer*

Synopsis

This paper reviews the use of crush pillars on mines in the Bushveld Complex and the Witwatersrand Supergroup. Stress measurements were undertaken in order to determine the residual strength of these crush pillars. The results from these stress measurements are compared with previous attempts to determine the residual strength of crush pillars using back analysis. It is concluded that the residual strength of such crush pillars lies in a band between 13 MPa and 25 MPa. Using the data from the stress measurements, as well as published and unpublished data, a stress-strain curve for a crush pillar with a width-to-height ratio of 2:1 is proposed. Where further work is required, this is indicated in the text.

Introduction

The stoping of tabular platinum orebodies in the Bushveld Complex and tabular gold orebodies at depths of less than 1 000 m in the Witwatersrand has to a large extent been accomplished by using in-stope pillars to ensure stability of the workings. These pillars ensure that sufficient support resistance is applied to the hangingwall to preclude the type of tensile failure of the hangingwall known as a 'backbreak'. Backbreaks occur when an under-supported hangingwall rock mass fails at large stoping spans and can involve rock failure 20 m or 30 m above the stoping horizon. This paper describes how the residual strength of crush pillars with a width-to-height ratio of 2:1 was determined by stress measurement. The measured results are then compared with earlier attempts to quantify the residual strength of these crush pillars by back analysis. A stress-strain curve of a crush pillar is then proposed and areas for further work are identified. Understanding how these pillar support systems behave in rock engineering terms is important in terms of safety and economics. Clearly it is important to optimally extract the orebody by not leaving excess ore locked up as pillars.

Historical perspective

Historically, in-stope pillars were widely used in the mining of the Witwatersrand gold reefs, but size was often arbitrarily determined and, in many cases, pillars became associated with rockbursting from mining depths of about 700 m (Pretorius). Perusal of plans of the early mining close to surface in the Bushveld Complex shows that pillars were left in stopes, but not necessarily in a systematic manner. Some of these shallow workings have collapsed but others, visited by the authors, are open and stable even today. With increasing depth, in-stope pillar systems became more common and were implemented systematically in the Bushveld platinum workings. A crush pillar system similar to that used today by many mines was introduced and described by Korf in 1978. He recognized that the stope collapse problem or backbreak that had plagued the Union Section mines resulted from the inadequacy of the passive and soft mat pack support system then being used. The support system was required to prevent separation of the 20 m thick hangingwall beam at the position of the Bastard Merensky Reef at mining spans of up to 80 m. The mat pack support system was incapable of supporting the required dead-weight. At a mat pack support spacing of 7.2 m and after 10% compression the stope support resistance was 70 kN/m² which was capable of supporting only 2.0 m of dead-weight. The implication is that the hangingwall rock mass was self-supporting prior to backbreak failure. Once a backbreak had initiated, the mat pack support system could not arrest the hangingwall. At a mat pack support spacing of 7.2 m and after 50% compression the support resistance of the mat pack support system would have been about 277 kN/m² which was capable of supporting only 8.5 m of deadweight.

Korf proposed the introduction of small 1.5 m by 3.0 m pillars below the strike gully in...
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order to prevent these backbreaks. In addition, he proposed that stiff 200 mm diameter mine poles should be used as support in the panels. The subsequent success of this pillar system was followed by the introduction of a similar system at Randfontein Estates Gold Mine in 1980. This mine was stoping at less than 1 000 m depth and was similarly plagued by loss of stopes due to backbreaks. The success of this strategy was described by Roberts in 1985. The practice of mining with an in-stope crush pillar support system has become common on platinum mines and shallow gold mines over the last 20 years.

The determination of the residual strength of crush pillars in the hard rock environment

Pillar terminology has not always been consistent over the years. It is necessary therefore to define the types of in-stope pillars commonly found in shallow Bushveld and Witwatersrand stopes. They can conveniently be classified into three types. These are represented schematically in Figure 1.

The first are intact pillars; these are pillars that have not yet reached the level of stress that would result in failure. They are typically used in shallow workings down to a depth of about 300 m, although one mining group has successfully used this type of pillar to a depth of 800 m.

The second are crush pillars, described above, with a width-to-height ratio of approximately 2:1. Because of their geometry, these pillars fail or crush passively shortly after being cut in the stope face. They can be orientated on strike or dip and these pillars would constitute about 5% to 7% of the total stoping area. After failure, such pillars still have a residual strength resulting from self-confinement within the failed reef or rock material. Crush pillars are mostly used at depths of greater that 200 m to 300 m where there is sufficient stope closure to cause failure relatively close to the working face.

Both these pillar systems are effective at preventing backbreak in shallow mines, with the implication that they both provide at least the required support resistance to the stope hangingwall to prevent backbreak. The support resistance generated by an in-stope crush pillar system will be lower than that generated by an in-stope intact pillar system.

A third type of pillar system that has been used in stopes, although less commonly today, is called the yield pillar system. The width-to-height ratio of these pillars is in the order of 4:1 or 5:1. The objective is for the pillar to yield at a stress close to the peak strength of the pillar. It has been the authors’ experience that the behaviour of these pillars can be unpredictable, and that pillar bursting can occur, compromising both safety and rock mass stability.

It was the objective of this research to determine the residual strength of in-stope crush pillars with a width-to-height ratio of 2:1. An evaluation of the residual strengths of crush pillars would allow the support resistance provided by the crush pillar support system in a stope to be determined.

An estimation of the support resistance provided by the crush pillar support system

Stress measurements at a Rustenburg mine

The stress measurements were undertaken at a mine in the Rustenburg area. The depth below surface was in excess of 1 000 m. The stoping width was approximately 1.8 m. It was realized that it would be impossible to measure the residual strength of the pillars within the fractured reef material. However, it was believed that stress measurements could be done in the intact rock above or below the crush pillars and that this would reasonably reflect the residual strength of the crush pillars. Boreholes were drilled above and below the crush pillars from a gully in order to conduct the stress measurements. The positions of the boreholes are shown as a schematic section in Figure 2.

Measurements were undertaken at two sites on the mine. On the western side of the mine two suitable in-stope pillars were identified and on the eastern side of the mine three suitable in-stope pillars were identified. The width of these pillars was approximately 3 m. The pillars selected had been subjected to considerable stope closure, in excess of 150 mm, and it was clear that the pillars had crushed. Figure 3 is a mine plan showing the position of the pillars on the western portion of the mine.

At both sites doorstopper stress cells were installed into boreholes drilled from the strike gully. A measure of the reliability of the readings was indicated by examining the degree of fracturing within the borehole cores. The experimental error was determined by calculating the difference between stress components, which should theoretically be equal (stress sums oriented at 0° and 45°).

![Figure 1—Schematic diagram describing the types of in-stope pillars](image-url)
The condition of the cores from the western and eastern sites are compared and shown in Figures 4 and 5. This comparison of core is a good indication of conditions at the two sites. No intact core was obtained from the eastern site where the pillars and the immediate hangingwall and footwall were badly damaged. The error computations confirmed that no reliable readings were possible at the eastern site. At the western site, closure of at least 150 mm had occurred, representing about 90 millistrains. Two boreholes were drilled and the stress measurements were undertaken in the hangingwall above the pillars. This rock was less damaged, as reflected by the intact core shown in Figure 4. An average experimental error of less than 10.6 % was determined.

The stress measurement results for the western site are presented in Table I. The recorded stress measurements were oriented such that the $yy$ direction represents the vertical axis. The results indicate five values for the vertical stress that cluster between 18 MPa and 21 MPa with a sixth value of 7.5 MPa. A seventh value was rejected as not reliable. A
The determination of the residual strength of hard rock crush pillars

Figure 4—The condition of borehole core from the western site

Figure 5—The condition of borehole core from the eastern site

<p>| Table I |
|------------------|------------------|-----------------|-----------------|-----------------|-----------------|
| Stress measurements from the western site |</p>
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weighted average was obtained by adjusting the contribution of each measured value based on the error calculated for that value. Using this method, the post-failure residual strength of the crush pillars can be inferred as 19 MPa.

Measurement of the mined area and pillars represented in Figure 3 shows that 96% extraction was achieved. If this extraction ratio is considered in terms of the residual strength of the crush pillars in the stope of 19 MPa, then the support resistance generated by the crush pillar stope support system would be 760 kN/m² or 0.76 MPa. This support resistance would be sufficient to support a dead-weight of just less than 23 m.

In reality, the residual strengths of the crush pillars shown in Figure 3 will not necessarily all be the same value of 19 MPa. Rather, the values would range between an upper and lower limit defining a band of residual strengths for crush pillars. Defining these limits, particularly the upper limit, is one of the recommendations for future work. However, there is some underground evidence that could give an indication of this upper limit. At a site at Randfontein Estates Gold Mine, the middling between a cross-cut and an overlying stope was 5.0 m. A strike line of crush pillars was situated over the cross-cut and orientated ninety degrees to the long axis of the cross-cut. The cross-cut was developed in poor quartzite with a UCS of about 75 MPa to 80 MPa. A stress concentration of about three could be expected in the corners of the cross-cut. No stress related damage, such as fracturing, was discernable anywhere in the cross-cut under the line of crush pillars. The implication was that the residual strength of the crush pillars could not be greater than one third of the UCS of the rock in which the cross-cut was situated. As this was known to be 75 MPa to 80 MPa, it was concluded the crush pillar residual strength was equal or less than 25 MPa. At this residual strength value the support resistance across the stope depicted in Figure 3 would be 1000 kN/m² or 1.0 MPa, capable of supporting a dead-weight of 30 m.

Previous estimates of the support resistance provided by a crush pillar support system and the crush pillar residual pillar strength

There have been previous attempts to determine the support resistance generated by crush pillar support systems and hence provide an estimate of crush pillar residual strength. These have been in the form of back analyses, which determine a minimum residual strength for the crush pillars. In both the cases described below, instrumentation such as extensometers and closure metres detected the hangingwall instability preceding a potential backbreak as the mining span increased. Subsequent instrumentation did not detect any hangingwall instability in the stopes at Randfontein when supported by crush pillars, or at Northam, where the placement of backfill halted the hangingwall instability.

Back analysis of data from Randfontein Estates Gold Mine

The observations at Randfontein Estates Gold Mine were made in the late 1970s and early 1980s where stoping was taking place without crush pillars. The stopes were supported with Mark 1 grout pack support systems, which provided insufficient support resistance to prevent backbreak. Extensometers and the monitoring of hangingwall excavations showed that the hangingwall failure extended up to 30 m into the hangingwall. In one case, the hangingwall was found to be affected 40 m above a collapsed stope. In 1980 crush pillars with a width-to-height ratio of 2:1 were cut in all new stopes and the backbreak problem unequivocally ceased. The actual crush pillar dimensions were 3.0 m wide on dip and 9.0 m long on strike. The mining height varied but averaged 1.5 m. Closure stations and extensometers installed in these stopes showed no inelastic movement in the hangingwall strata once the crush pillars were introduced. The crush pillars restricted stope closure to elastic convergence only. This was confirmed by comparing the measured closure in stopes to the modelled elastic convergence using the now defunct elastic numerical model DREEF.

In the stopes where backbreaks had occurred, the height of the hangingwall affected by backbreaks was known. It was therefore possible to back calculate the minimum support resistance provided by the newly installed crush pillar support system. This was determined to be 1.1 MPa. The percentage of pillars in stopes was 8%, allowing a minimum residual crush pillar strength to be calculated as 15 MPa.

Back analysis of data from Northam Platinum Mine

This work is of interest in that it shows that a support resistance of about 1 MPa is sufficient to stabilize a stope hangingwall and prevent the backbreak process from proceeding. The work at Northam is described by Roberts et al.5 The intention was to determine if the stope hangingwall was still prone to backbreak failure at a depth of 1 400 m. Conventional pack and elongate support was used to support the eight-panel stope and no pillars were cut. Instrumentation including closure meters and extensometers, was installed and the hangingwall was monitored with increasing mining spans. The extensometers showed substantial and increasing dilations between layers up to 28 m in the hangingwall. The magnitudes of these dilations could not be accounted for by the elastic response of the hangingwall rock alone. The dilation and some of the stope closure component were therefore inelastic, which indicated that the hangingwall was becoming unstable and that backbreak was inevitable with increasing mining spans. For this reason, all panels were then backfilled and stoping continued. Stress measurements in the backfill were then undertaken as the mining spans increased further. When the backfill was installed, the extensometers in the hangingwall continued to show dilation until the backfill had strained to about 12% and reached a measured vertical stress of about 1.0 MPa. At this point, hangingwall deformation became elastic and the hangingwall stabilized. This indicates that a stope support resistance of 1.0 MPa was sufficient to stabilize the stope hangingwall.

The stress-strain curve of a 2:1 crush pillar

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The stress-strain curve of a 2:1 crush pillar

The stress-strain curve of a 2:1 crush pillar can be constructed with some confidence based on the work described above. However, there are parts of the stress-strain curve where uncertainties remain. Figure 6 is the stress-strain curve, which represents a crush pillar with a width-to-height ratio of 2:1. In the section below the various portions
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The amount of stope closure that is required to occur for the pillar to reach its ultimate strength at B has been both estimated from laboratory testing and measured underground. In a number of UCS tests of quartzites and pyroxenites, failure under direct compression occurs at about 3 millistrains. The specimens have a width-to-height ratio of 1:2.5. In the case of crush pillars, which have a width-to-height ratio of 2:1, it can be assumed that the vertical strain at failure will be greater than 3 millistrains as there is greater confinement. The second author of this paper has measured closure between two pegs recessed in hollows in the hangingwall and footwall next to a pillar being cut from the face. The stope closure was read using a vernier measuring device. After the stope closure next to the pillar amounted to 10 millistrains there were the first visual indications that the pillar had reached its ultimate strength, B, and had failed. In addition, Roberts and Jager have proposed failure of these pillars at a vertical strain of 6 millistrains. It is therefore proposed that A would have a range of 3 millistrains to 10 millistrains. This assumes that the hangingwall and footwall rock mass is considerably stronger than the material making up the pillar. This is not always the case, as at Beatrix Gold Mine and some Bushveld mines, where pillars with a width-to-height ratio of 2:1 initially punch the weak footwall rock mass. With increasing stope closure, footwall punching becomes increasingly difficult and the pillar then fails. In this situation, the value of A can be as large or larger than the 50 millistrains indicated in Figure 7. Clearly, further insights are required to understand crush pillar systems that behave in this way.

The value of the ultimate strength of the pillar, B, in Figure 6 can also be estimated by using the correction factors described by Ryder and Ozbay. The UCS of the pillar material is multiplied by these factors in order to determine the ultimate strength. These factors are as follows:

- Size factor: 0.2 to 0.5
- Shape factor: 1.0 (square) to 1.4 (rectangular)
- First width-to-height factor: 1.3
- Second width-to-height factor: 1.0 to 1.6

To determine B for the Randfontein Estates Gold Mine crush pillar support system described above, the following apply. The UCS was 210 MPa, the pillar size was 3 m by 9 m and the mining height was 1.5 m.
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B = UCS x size factor x shape factor x first width-to-height factor x second width-to-height factor.

B = 210 x 0.4 x 1.15 x 1.3 x 1.2 = 151 MPa.

At the Rustenburg mine where the stress measurements were performed, a number of UCS tests were undertaken. The UCS varied between 85 MPa and 120 MPa, averaging about 105 MPa. Deriving B as above finds B = 75 MPa. The Ryder and Ozbay method of estimating B is relatively crude and there could be scope for stress measurements to be undertaken in order to refine the correction factors. The size and width-to-height factors are particularly uncertain for Bushveld rocks and the strength determined here could be underestimated.

The post-failure slope at position C, Figure 6. The stiffness of the strata must be greater than the post-peak stiffness (post-failure modulus) of the pillar, or violent pillar failure and hangingwall instability will occur. This is confirmed by the observation that many thousand of pillars with a width-to-height ratio of 2:1 have been cut, and violent failure of these pillars has been extremely rare. The concept of strata stiffness is complex but adequately explained by Ozbay and Roberts. Here the post-peak stiffness of the pillars is defined as λ, and the critical strata stiffness as λr. If λ > λr, the pillars are crushed and stable. Examples are given in the paper of post-peak pillar stiffness for pillars of different width-to-height ratios (Figure 1). The pillar in which the residual strength was measured is estimated to have a post-peak pillar stiffness of λ = -12.0 GN/m. This post-peak pillar stiffness was determined for a stress drop of 75 MPa to 19 MPa within 5 millistrains of deformation.

Position D, Figure 6, which has been the main subject of this paper. The measured residual pillar strength was 19 MPa following approximately 90 millistrains of closure. The back analyses indicated that the strength could be less than 25 MPa, and as low as 13 MPa. Therefore, it is proposed that the residual strength of a crush pillar with a width-to-height ratio of 2:1 could lie in a 13 MPa to 25 MPa range. More measurements are required to define this range more accurately. It is acknowledged that different geotechnical conditions will also affect crush pillar performance parameters. The sensitivity of crush pillar systems to geotechnical parameters was partially addressed by Roberts, et al.

Position E, Figure 6. Severe footwall heave around crush pillars has been noted when a large amount of stope closure has occurred. Crush pillars, originally with a width-to-height ratio of 2:1, become squat in the back areas of stopes at large mining spans as they have been subject to high amounts of stope closure. Severe footwall lifting has been noted around these pillars where stope closure has imposed a vertical strain of 0.47. This clearly indicates that the residual strength has increased. It is, however, not known at what strain the increase in residual strength becomes manifest. Monitoring a stress cell installed in the hangingwall or footwall of a crush pillar subject to increasing stope closure could determine this. It can be stated though that the residual pillar stress increases at E where the vertical strain is greater than 0.4. In this region, the slope of the stress-strain curve will be positive.

Figure 8 is a depiction of the stress-strain graph of a crush pillar at the western stress measurement site using stress or strain values discussed above. The strain at the initial intact pillar strength is the middle of the 5 millistrain to 10 millistrain band. The pillar strength is 75 MPa. The post-peak pillar stiffness is -12.0 GN/m. The residual strength is 19 MPa as derived from the stress measurements. At a strain of 0.4 the residual pillar stress is not known but it is assumed that the stress increases with further deformation.

This is a representation of the full stress-strain curve of a 2:1 crush pillar based on the best information currently available. It is believed that the proposed range of crush pillar residual strengths is based on reliable measurements and sound scientific extrapolation of observed behaviour. Estimates of strains at failure are also based on real observations and the suggested range is believed to be reliable. The greatest uncertainty in this evaluation is in the estimation of the peak pillar strength, which is entirely theoretical and may not be applicable to Bushveld rockmass conditions.

Conclusions

The residual strength of two crush pillars with a width-to-height ratio of 2:1 has been measured at a platinum mine in a Merensky Reef stope. A value of 19 MPa was determined.

A review of earlier estimates of the residual strength of crush pillars, the measured value of 19 MPa and underground observations leads to the conclusion that the residual strength of crush pillars lies between 13 MPa and 25 MPa.

The stress-strain curve for such a crush pillar is proposed.

Figure 8—A depiction of the stress-strain graph of a crush pillar at the western stress measurement site.
The determination of the residual strength of hard rock crush pillars

➤ The further technical work that is required to confirm and extend these findings is specified in the text of the paper.

Acknowledgements

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References

It’s been pretty good news all round for the average Australian ‘hip pocket’ just lately. Personal income taxes are down and wages are up—good if you’re a worker.

But if you are out there earning a good income as a professional in the mining industry, for example, and you want to upgrade your skills with postgraduate study, it can be a hard call to take a pay cut to chase a three-and-a-half year PhD.

The decision is largely economic, but the JKMRC—a world-leading minerals engineering research centre with The University of Queensland—has announced a scholarship scheme aimed at making the decision a lot easier.

The JKMRC’s Education Manager Dr Dominic Howarth has announced a scholarship package worth up to A$40 000, with a base level of A$25 000, effective immediately for anyone gaining access into a master’s or PhD research programme through UQ’s JK Centre based in Brisbane. And it’s all tax free.

To encourage young professionals to upgrade their technical skills, an additional A$3 000 for each year of approved work experience prior to starting a postgraduate degree will be added to their base level scholarship up to a maximum of five years.

All scholarships are CPI indexed to keep up with the cost of living, and the JKMRC will pay all tuition fees for international students.

As Dr Howarth explained, the JKMRC has a large international cohort of students, making the JK Centre uniquely multicultural. Current students at the JK Centre come from Australia, Canada, Chile, China, Ghana, Indonesia, Malaysia, Mexico, South Africa, the United Kingdom and the USA.

‘The minerals industry worldwide just can’t get enough specialist mineral processing professionals,’ Dr Howarth said. ‘Postgraduate education is the industry’s lifeblood.’

Dr Howarth said JKMRC postgraduates—typically PhD and master’s—had a worldwide reputation in the mining and minerals processing fields, often going on to senior and executive level technical positions. Global companies such as Rio Tinto, BHP Billiton, Xstrata—as well as leading research organizations—have JKMRC graduates among their senior ranks.

Dr Howarth said anyone wanting to know how to get involved in a JKMRC postgraduate programme should check the web at www.jkmrc.uq.edu.au, or phone the JK Centre on +61 7 33655888, or send email enquiries to jkmrc@uq.edu.au

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