Crush Pillars' Behaviour at Intermediate Depth on Merensky Reef

Hlomani Mthombeni
Rock Engineering Department, Sibanye-Stillwater Siphumelele Rustenburg, South Africa, South Africa

Shane Durapraj
Rock Engineering Department, Sibanye Stillwater SA PGM, Rustenburg, South Africa

Richard Masethe
Rock Engineering and Seismology Department, Sibanye-Stillwater Limited, Libanon, South Africa

ABSTRACT: The Siphumelele Mine orebody has been mined extensively up to a depth of up to 1400 m below surface. Apart from stope support, stability of the reef horizon is provided by regional stability pillars support as well as local "crush pillar" support. These pillars are designed so that they crush as they are being cut, with the residual strength of the pillar material being used for the design. However, the major challenge is to "cut" or mine these pillars to the designed size. Undersized pillars degrade and do not provide the required stability, whilst pillar bursts may occur from oversized pillars. Correctly cut pillars perform as expected; they fracture and provide the necessary support.

Keywords: Crush pillars, w:h ratio, rockburst, support.

1 INTRODUCTION

Siphumelele Mine, owned and operated by Sibanye Stillwater, is an intermediate-depth platinum mine in the western limb of the Bushveld Complex, located 20 km east of Rustenburg. Two thin seam platinum-bearing reefs are exploited, viz., Merensky (0.3 m) and UG2 (0.7 m). The Merensky Reef has a higher grade value and has been mined extensively at Siphumelele Mine up to depths of 1400 m below surface. Despite its intermediate depth, significant stope closure, seismicity and moderately high stress occur. Furthermore, it is expected that the excavations are surrounded by an envelope of fractured rock (Jager & Ryder, 2001).

One of the strategies to promote stability in the fractured rockmass is to use crush pillars; those pillars at residual strength that provide load-bearing ability. As the mining front advances, these pillars are cut (Figure 1) in a sequential manner. Both the fractured rockmass, as well as poor blasting practices, contribute to either over-or-undersized pillars. An oversized crush pillar is characterised by a width-to-height (w:h) ratio greater than 3.0, which is susceptible to rockbursts, whilst an undersized crush pillar has a w:h ratio of less than 2.0 (Ozbay, Ryder, & Jager, 1995), may degrade over time. A further design criterion is that the load carried by these crush pillars should support a beam of 12 m above the reef contact i.e., up to the bastard reef bottom contact, which may have a cohesionless surface to the rockmass above. At Siphumelele the case study concentrated on an analysis of the behaviour of the crush pillars in relation to their dimensions and the impact on the stope condition if the pillar was cut incorrectly.

2 CRUSH PILLAR DESIGN IN SCATTERED BREAST MINING LAYOUT

The Siphumelele Mine employs the underhand mining sequence, in which the panel above leads the panel below in a raise line. Regional dip pillars, of 20-24 m wide, are left in-situ to provide regional stability between two production raise lines. The crush pillars are cut along the strike of the orebody, between two panels, just below the north-siding of the panel above (Figure 1). The mine standard requires that the upper panel mine no more than 15 m ahead of the panel below. In addition, the siding must not be more than 4.0 m behind the panel face and must mine for at least 3.0 m on dip from the Advanced Strike Gully Centre (ASG) centre line (Sibanye Stillwater, 2019). The siding has several advantages in that a) it reduces the effective height of the pillars, which is indirectly proportional to crush pillar strength; b) it reduces the amount of rock mass exposed to high induced stress along the ASG sidewall; c) any "failure" of the pillar will not affect the ore recovery ASG and d) the persons are not directly exposed to any pillar failure. If the siding lag is greater than the lag of the panel below, an oversized pillar stub may be formed.

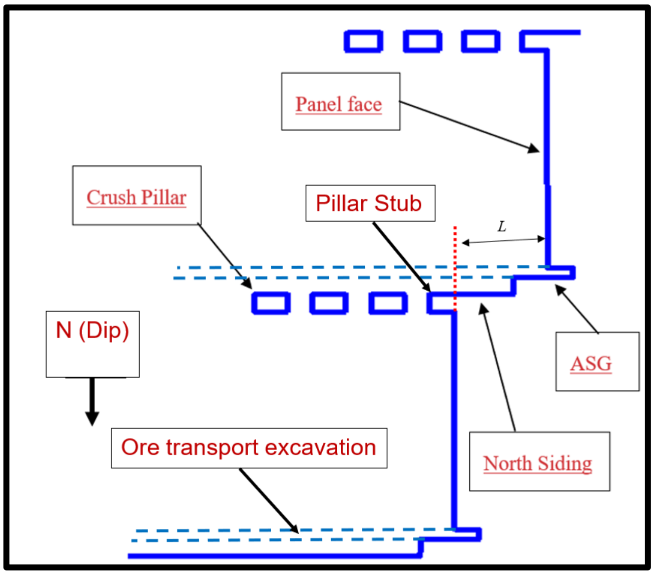

Figure 1. Panel configuration for Merensky reef including sidings (Not to Scale). *L* represent the panel lead.

The crush pillar design for Siphumelele Mine was based on empirical designs from other mines, established theoretical criteria, and the requirement to alter the dimensions and spacing of the pillars (Ozbay, Ryder, & Jager, 1995), to meet the required performance. Therefore, the crush pillar has been designed with a width of 2.5 m (along dip) and a length of 4.0 m (along strike). The crush pillars are separated by a 3.0 m wide holing (measured along strike), for access and ventilation purposes. Authors have indicated that the crushing allows the pillar to achieve its residual strength, which is crucial for back area support to be achieved (Du Plessis & Malan, 2018) and that, once the pillar is crushed it achieves its residual strength through self-confinement within the failed rocks (Roberts D., 2005). Watson et al. (2010) also carried out a back-analysis investigation of pillar failures at Impala Platinum Mines and developed an empirical formula to determine peak pillar strength in the Merensky Reef. The investigation was conducted at a depth of 600 metres and was found to be applicable to a depth of 1500 metres. The empirical formula is shown in Equation (1) (Watson, Kuijpers, & Stacey, 2010):

$$Pillar\ Strength = 136\left[\frac{1.27}{1+\frac{0.27(w)}{L}}\right]\left[0.59 + 0.41\frac{w}{h}\right] \quad (1)$$

Where:
L is the pillar length
w is the crush pillar width
h is the stoping width or pillar height
For Siphumelele Mine L = 4.0 m, w = 2.5 m and h = 1.0 m, and therefore using the empirical formula, the pillar peak strength was determined as:

$$Pillar\ Strength = 136\left[\frac{1.27}{1+\frac{0.27(2.5m)}{4.0m}}\right]\left[0.59 + 0.41\frac{2.5m}{1.0m}\right] = 238.67 \text{ MPa}$$

It should be noted that the back analysis investigation determined that Equation (1) only has a 50% probability of failure (Watson et al., 2010). The available loading must be greater than the pillar strength calculated in Equation (1) for the probability of failure for a crush pillar to increase. To ensure fracturing, a crush pillar must have a factor of safety (FOS) of less than 1 (Watson et al., 2010). FOS is defined as the ratio of pillar strength to pillar stress. Du Plessis and Malan,2018, conducted a similar investigation of pillar stresses in a similar geotechnical environment. The investigation was carried out at a depth of 1300 m in a mine using crush pillars on the Merensky reef. The panel face length was also 35.0 m, and the dimensions of the crush pillars were identical to those implemented in Siphumelele Mine. Figure 2 depicts the stresses acting on a pillar in relation to its distance from the panel face.

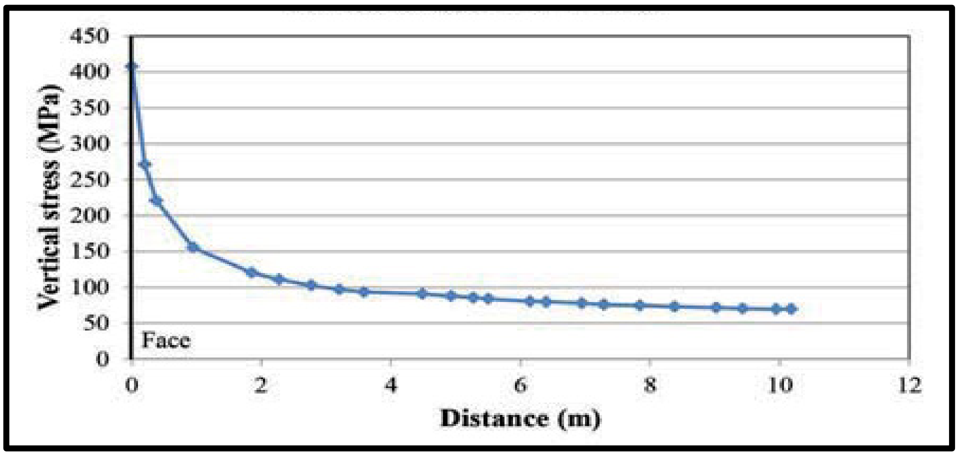

Figure 2. Graph showing vertical stress acting on the crush pillars in relation to their distance from the face at 1300mbs (Du Plessis & Malan, 2018).

Because of the high abutment stresses acting on the panel face, the stresses are higher closer to the panel face. The high stresses on the panel faces are what cause the pillars to crush/fracture. The pillars continue to fracture as the panel face advances, until the pillar reaches the required residual design strength to support the stope.

3 PILLAR CUTTING MONITORING

In order to monitor whether stopes are stable, as per the design, a monthly pillar cutting compliance report is produced. Only pillars with a w:h ratio of 2.0 to 3.0 are determined to have been cut correctly. Crush pillars with a w:h ratio of less than 2.0 are undersized, and the ones with a w:h ratio higher than 3.0 are oversized. Through the scrutiny of old mine plans of mined-out working areas, it was evident that pillar cutting has been a challenge. Drilling and blasting practice, marking of the panel, and direction lines are some of the factors affecting pillar-cutting compliance. Over a 12-month period, compliance has averaged 70%. This infers that 30% of the pillars that are cut each month do not conform to the design and as such are either oversized or undersized.

Table 1. 12 Month Pillar Cutting Performance (Sibanye Stillwater SA PGM, 2022).

Pillar-Cutting Performance - average		
Correctly Cut	Incorrectly Cut	
70%	30%	
	Oversized = 77%	Undersized = 23%

The major (77%) non-conformance is from oversized pillars. As indicated earlier, rockbursting is a possibility at this depth, as an oversized crush pillar accumulates stress without fracturing, thereby storing a large amount of strain energy, that may be susceptible to dynamic release of loading. This could result in damage to workings and/or injury to persons.

To observe the fracturing behaviour of under-or-oversized crush pillars, underground investigations (Figure 3) were conducted at various sites. Two sites at the mine, 34LE-42-4W and 33LW-10-2W, were chosen as the pillar observation sites. The 34LE-42-4W had both undersized and oversized pillars in one panel. The dimensions of the pillars at 33W-10-2W were correct.

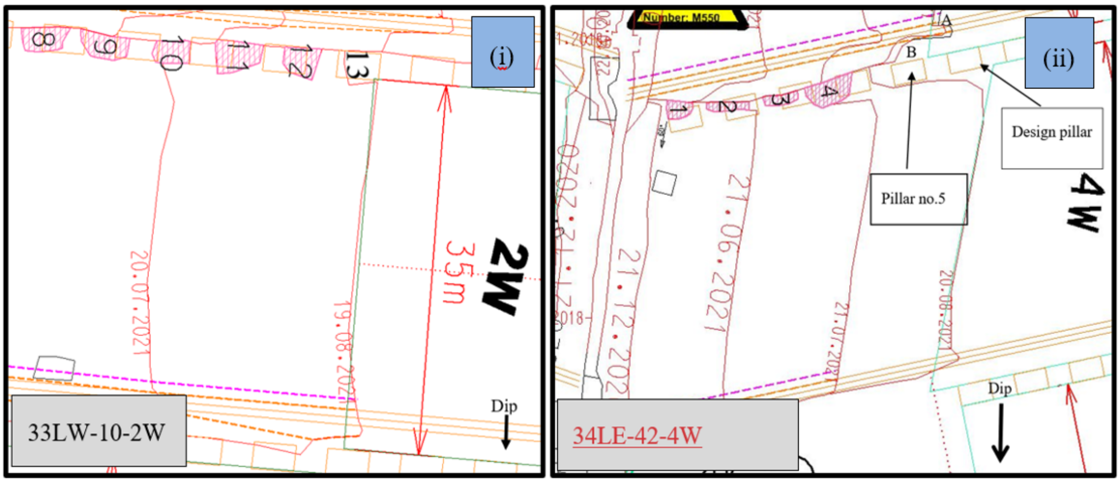

Figure 3. (i) Stope 33LW-10-2W including crush pillar number 8-13 and (ii) Stope 34LE-42-4W with crush pillar 1-4 plans33LW-10-2W Observations.

The 33LW-10-2W plan (Figure 3(i)) shows the in-situ cut pillars versus the designed pillars. Pillar numbers 10, 11, 12, and 13 (Figure 4) were observed for the purposes of this project. Pillar No.13 was not fully established; it was still a pillar stub, and a pillar holing was still yet to be cut to complete the pillar.

The underground investigation revealed that:

- The crush pillar starts to scale while it is still being formed, and fracturing can be observed around the edges of the pillar. This applies to crush pillars with width to height ratio of between 2.0 and 3.0. Pillar No.13 (pillar stub) in Figure 4 shows more defined fractures on the side of the north siding.
- For an established cut pillar 12, area of 8.2 m^2, perimeter of 11.5m and a measured height of 1.1 m reveals the:

$$w_{eff} = (4 \text{ x Area of pillar})/\text{Perimeter of pillar} = \frac{4\,x\,8.2m^2}{11.5m} = 2.85m$$

Therefore, the w:h ratio = 2.85:1.10 = 2.6:1 or simply 2.6

- The side of the pillar that was exposed first has more fractures than the side of the pillar that was exposed at a later stage. The fractures are better defined on the side of the pillar that was exposed for a longer period (Du Plessis & Malan, 2018).

Figure 4. Pillar 13 showing more fracturing on the north siding side due to prolonged exposure.

Figure 3(ii) shows the plan of the 34LE-42-4W panel, indicating pillars that have been cut versus the designed pillars. Pillars no. 1 to 3 are undersized and pillar no.4 was oversized. Pillar no. 5 (pillar stub) was not established because the panel above was permanently stopped at position ‘A’ in Figure 4(ii) and its siding was stopped at position ‘B’, thus not allowing for an establishment of another pillar holing or a fully cut pillar. This created an oversized partially cut pillar no.5. Figure 5 show photographs of the pillars.

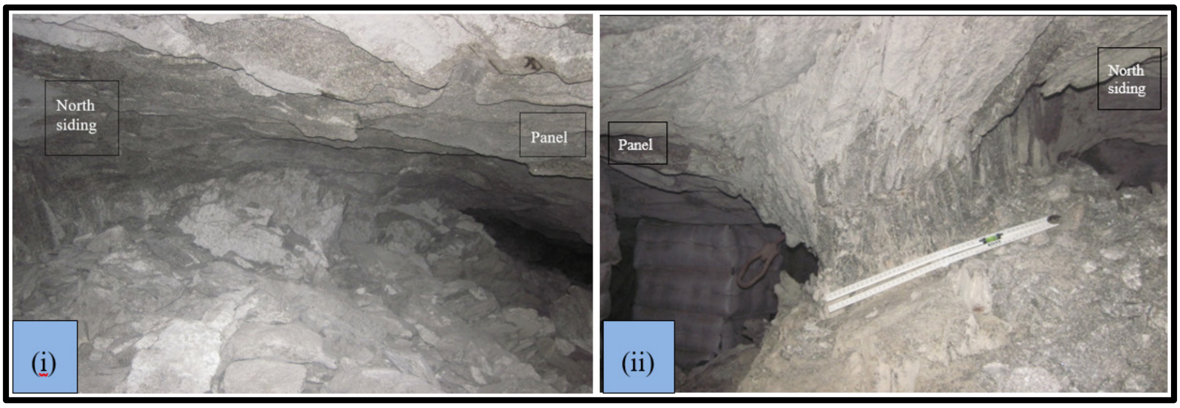

Figure 5. (i) Pillar no.5 after a strain burst triggered by a seismic event, (ii) Undersized pillar no.2.

The underground investigation noted that:

- As indicated previously, at this depth, the oversized pillars (Pillar No.5 – Figure 6(i)) may burst. A M_L 0,1seismic event, located 260 m away resulted in the damage seen here. Note that the oversized pillar showed no fracturing or any signs of crushing even after it burst; only the ejected rocks were visible.
- In contrast, the undersized pillars (Figure 5(ii)) scale beyond the design limit and provide little to no back area support. These pillars are less prone to bursting.
- For an undersized pillar (Pillar No.2), with an area of 5.4 m^2, perimeter of 12.5 m and a measured height of 1.18 m,

$$\text{the } weff = (4\,x\,Area\ of\ pillar)/Perimeter\ of\ pillar = \frac{4\,x\,5.4m^2}{12.5m} = 1.7m$$

Therefore, the width to height ratio = 1.7:1.18 = 1.44:1 or simply 1.4, which is below the w:h ratio of 2.

4 ANALYSIS OF RESULTS

- Mining of a siding improves the pillar strength by reducing the effective height of the pillar. This makes it easier to control the w:h ratio and has several advantages including that the pillar fractures as per design.
- The design pillar strength was determined to be less than the stress acting on pillars closer to the face. The factor of safety is less than 1, thus ensuring that fracturing occurs.
- The stress acting on the crush pillars is relatively higher closer to the face because of the abutment stress. This is necessary to increase the probability of failure of the crush pillar. The fracturing of the crush pillar continues as the panel face advances, until the crush pillar achieves its residual strength.
- Oversized pillars increase the risk of dynamic failure of the pillar.
- Pillars that have been cut correctly in the Merensky reef at this depth with a 2.5 w:h ratio perform better than oversized or undersized pillars. The w:h ratio range of the crush pillars at 2.0-3.0 was proved correct.
- Undersized pillars do not carry the required load and provide little support in the back areas.
- Changes to the sidings relative to stopped panels will need revision as these impacts on the pillar dimensions. Oversized stubs should be planned out or mitigation put in place to prevent oversized pillars.

5 CONCLUSION

When designing and executing the crush pillar design, the width-to-height ratio is critical to the pillar performance and impact. The study has shown that undersized crush pillars will not achieve the required residual strength and the required load-bearing ability, whilst oversized crush pillars may be prone to dynamic failure. Evidence has shown that correctly cut pillars perform as designed; they will fracture in a controlled manner as they are cut and perform the required local support function. It is imperative for the mining discipline to take note and improve their mining discipline to improve the safety of individuals and prevent damage to workings.

REFERENCES

du Plessis, M. (2015). *The Design and Bahaviour of Crush Pillars on the Merensky Reef.* Pretoria: University of Pretoria.

du Plessis, M., & Malan, D. (2018). Mining with crush pillars. *The Journal of the Southern African Institute of Mining andMmetallurgy, 118*, 212-214.

Jager, A. J., & Ryder, J. A. (2001). *A handbook on Rock Engineering Practice for tabular hardrock.* Johannesburg: The Safety of Mine Research Advisory Committee.

Ozbay, M. U., Rydar, J. A., & Jager, A. J. (1995). The design of pillar systems as practised in shallow hard-rock tabular minesin South Africa. *The Journal of The South African Institute of Mining and Metallurgy*, 10-11.

Roberts, D. (2005). The determination of the residual strength of hard rock crush pillars with a width-to-height ratio of 2:1. *The Journal of The South African Institute of Mining and Metallurgy, 105*, 405.

Sibanye Stillwater. (2019). *MANDATORY CODE OF PRACTICE - COMBAT ROCK FALL AND ROCK BURST ACCIDENTS.* Rustenburg: Sibanye Stillwater.

Sibanye Stillwater SA PGM. (2022). *Siphumelele 1 Shaft Technical Support Document Merensky BP 2022.* Rustenburg: Sibanye Stillwater.

Watson, B. P., Kuijpers, J. S., & Stacey, T. R. (2010). Design of Merensky Reef crush pillars. *The Journal of The Southern African Institute of Mining and Metallurgy*, 582.