# The design of pillar systems as practised in shallow hard-rock tabular mines in South Africa

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**Synopsis**

*This paper deals with procedures used for designing pillar systems in hard-rock tabular mines operating at shallow depths, typically less than 1000 m. A comprehensive review of current practice identifies four types of pillars, namely non-yield, yield, crush and barrier pillars, and the main principles for designing these pillars are outlined. It is shown that the current design methods for pillar systems in South Africa are mainly empirical, each mine developing its pillar-design methods based largely on practical experience. This results in varying pillar layouts, even between neighbouring mines, despite similarities in geology, and depth of mining. It is suggested that some current layouts may fall short of being the best as regards safety, the maximum safe extraction percentages, or flexibility in accommodating future mining scenarios in deeper or otherwise different geological conditions.*

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## Introduction

Pillars have been used as stope support since the early days of mining, and they remain the main support component in most present-day shallow tabular mines. The compelling need for using pillars is dictated by the prevailing considerations of rock mechanics at shallow depths, namely the large tensile stresses in the hangingwall, and geological weaknesses in the hangingwall rockmass.

The hangingwall of any mining excavation is subjected to vertical 'deadweight' tensile stresses. In the case of tabular excavations, according to elastic theory, the extent of the tensile zone becomes larger with increasing ratio of mining span to the mining depth (*L/H*) and smaller with increasing ratio of the horizontal to vertical components (*k*) of the virgin stress tensor. The variation in the extent of the tensile zone over a 200 m span stope, as a function of increasing depth, is shown in Figure 1, where the *k* ratio is assumed to be high near surface but falls off realistically with depth. It can be seen that large portions of the hangingwall (50 m or more) can be subjected to vertical tensile stresses. In contrast, at great depth (>1000 m), not only is the tensile zone smaller but horizontal 'clamping' forces generated by face fracturing tend to render the hangingwall virtually self-supporting.

At shallow depths, there are usually joints and bedding planes which weaken the hangingwall rockmass. For example, in the south–west region of the Bushveld Igneous Complex (BIC), the hangingwall of the Merensky Reef typically contains two major weak parting planes. At 2 to 4 m there is a weak pyroxenite–norite transition, and at 10 to 15 m there is a well-defined parting at the Bastard Merensky Reef contact. In many cases, these parting planes are segmented by vertical joint systems which are mostly developed sympathetically to the faults and dykes.

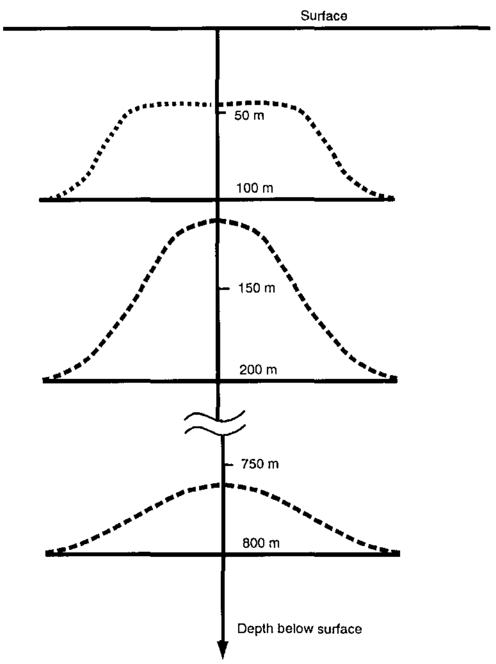


**Figure 1—Tensile zone above 200 m stopes at depths of 100 m, 200 m, and 800 m. Virgin stress components $\sigma_v$ (vertical) and $\sigma_h$ (horizontal) are taken as function of depth H: $\sigma_v$ = 0,03H; $\sigma_h$ = 30 + 0,01H**

The hangingwall in shallow hard-rock mining situations can then be characterized as a rockmass containing well-defined discontinuities subjected to deadweight tension. When unsupported, the hangingwall becomes susceptible to 'backbreaks' if critical spans are exceeded. In very shallow situations, hangingwall collapses can extend up to the surface, and the full weight of the rock on the overburden may be involved in a potential collapse. These conditions require a support system which is not only robust but which is stiff and can react rapidly under relatively little convergence. Depending on the extent of the tensile zone and position of critical weak parting planes, the support resistances required are in the order of 300 to 1200 kN/m$^2$, for 10 to 40 m of hangingwall requiring support. As indicated in Figure 2, in-panel support requirements in most cases cannot be met by using only conventional support systems, such as props, sticks, or even grout packs. Collapses

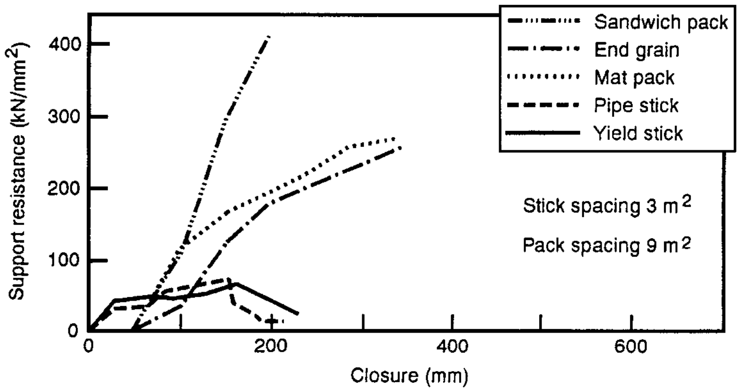


**Figure 2—Support resistance of various pack and stick support as a function of closure[8]**

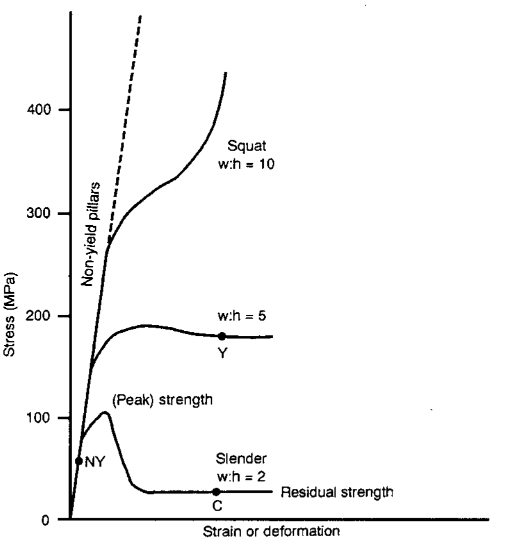


**Figure 3—Typical stress-strain behaviour of hard rock pillars of different width-to-height ratios. Typical operating points are shown for NY (non-yield and barrier), C (crush), and Y (yield) pillars**

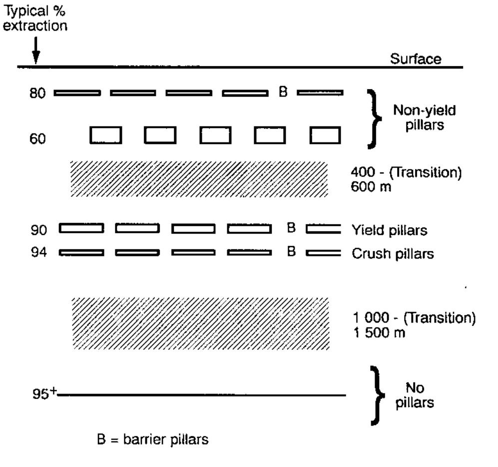


**Figure 4—Typical pillar-mining systems at different depths (B = barrier pillar)**

have been experienced in practice, where stick supports on 1 x 1 m spacing could not prevent collapses once the integrity of the hangingwall was lost. Only backfill or pillars of unmined ore can provide the required support resistance, and almost all shallow hard-rock mines currently use pillars which are better known, and generally cost less than other methods.

## Types and design of pillars as practised in shallow mines

Based on the review of current shallow-mining practice, four types of pillars can be identified. These are non-yield, crush, yield, and barrier pillars, and their typical operating characteristics are shown in Figure 3. The typical depths at which these various pillar types may be exploited are indicated in Figure 4. Further details of these types of pillars and their design are discussed in the following sections.

### *Non-yield pillars*

At very shallow depths, the tensile zone in the hangingwall can extend up to surface, and under these conditions the design of pillars is similar to the design of bord-and-pillar systems in coal mining. The main consideration is to ensure that the strength of pillars at all times exceeds, by a suitable factor of safety, the maximum average pillar stress (APS) imposed by the cover load of superincumbent strata. These pillars, which are intended to remain essentially intact and elastic during the life of the mine, will be called *non-yield* pillars, and have stress/strain characteristics shown by the *line* indicated in Figure 3. The width-to-height ($w/h$) ratios of these pillars are on occasions as low as 0,7 at very shallow depths, but are more usually in the range 2 to 5 and even higher.

The most important parameter in designing non-yield pillars is the pillar strength, $\sigma_s$. Currently, the strength of pillars is usually estimated using a modified version of the empirical formula proposed by Salamon and Munro[1] for coal pillars, which is in the form of:

$$\sigma_s = K\, h^{\alpha}\, w^{\beta}, \qquad [1]$$

where $\sigma_s$ is the pillar strength (MPa), $h$ and $w$ are the height and width of a pillar (m), and for South African coal fields, $K$ = 7,2 MPa (strength of 1 m$^3$ coal), $\alpha$ = -0,66 and $\beta$ = 0,46. A modified version of this formula, known as the squat-pillar formula, is used to reflect the very rapid increase in strength of support pillars having $w/h$ ratios greater than approximately 5.

In the literature describing hard-rock mining practice using pillars, the method of selecting a value for $K$ is not consistent. The values used for $K$ vary from $K$ equal to the Ultimate Compressive Strength (UCS) to $K$ equal to one-third of the UCS. The application of the Hoek-and-Brown rockmass-strength criterion[2] to the reef UCS is also used as indicated in the formula:

$$\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + \sigma_c^2 s)^{0,5} \qquad [2]$$

which predicts the unconfined rockmass strength for 'good quality' rock that comprising a pillar to be

$\sigma_1 = 0{,}32\ \sigma_c$,
for $s = 0{,}1$ and $\sigma_3 = 0$.

where

$\sigma_1$ is the rockmass strength,
$\sigma_c$ is the laboratory UCS,
$\sigma_3$ is the confining stress, and
$m$ and $s$ are the material constants as described by Hoek and Brown[2].

For hard-rock pillar design, the values of the exponents $\alpha$ and $\beta$ are most commonly taken as $-0{,}75$ and $0{,}5$, respectively. These particular exponents appear to be from a study by Hedley and Grant[3], and popularized by Wagner and Salamon[4] as quoted in Kersten[5]. Hedley and Grant's work is based on a back-analysis of pillar workings at the Quirke Mine, Elliot Lake, where the orebody is stratified conglomerates, and hanging- and footwalls consist of layered quartzite, argillite, and limestone formations. It is important to note that the exponents were actually derived by considering a relatively narrow range of $w/h$ ratios, typically between 0,7 to 1,5. Current experience in South Africa is also beginning to suggest that for certain high-friction rocks (such as pillars made up of UG2 reef or chromitite seams), the $w/h$ ratio strengthening may be much greater than indicated, with an equivalent value of $\beta$ ranging up to 1,0 or more.

Pillar stresses are normally calculated using the Tributary Area Theory (TAT), which accounts for the full cover load, i.e.

$$A = \frac{q}{1-e} \qquad [3]$$

where

$A$ is the Average Pillar Stress (APS),
$q$ is the vertical component of the virgin stress, and
$e$ is the areal extraction ratio.

The TAT method assumes that the lateral extent of mining is several times greater than the mining depth, so that the pillars carry full cover load. It is operationally convenient as it leads to fixed pillar-design dimensions for any given seam material and depth. The TAT method tends to be conservative, considering the fact that the pillars near permanent abutments or lines of regional pillars carry lower stresses than the TAT method predicts, regardless of the extent of mining. Also, in practice, potholes or fault losses are often left as unintentional pillars, resulting in lower extraction ratios, thus lower APS values, than initially planned.

Numerical models, e.g. two- and three-dimensional boundary element computer programs, are often used for determining APS for irregular layouts. However, these models do not currently provide simple procedures for determining APS and may require onerous computer-run times, or intricate additional calculations for accurate APS determination. Additional features to these models are required for obtaining accurate and quick determinations of APS.

The standard value of 1,6 for the Factor of Safety (FS) used in South African coal-mine rock engineering is also used in hard-rock mining. Ryder and Ozbay[6] suggested that, in hard-rock mines, the FS needs to be individually selected, and values for FS < 1,3 are not advisable unless regional stability levels are well established. Hedley and Grant[3] proposed values of FS = 1,5 based on their back-analysis, as shown in Figure 5.

Kersten[5, 7] developed an empirical method for pillar design based on back-analysis, and utilizing a spread-sheet program for carrying out the calculations. In his method, four different pillar-states are defined, namely: intact, slight slabbing, intense slabbing, and failed. After classifying pillars, the APS values acting on them (prior to failure) are estimated using TAT methods and then a value for $K$ can be

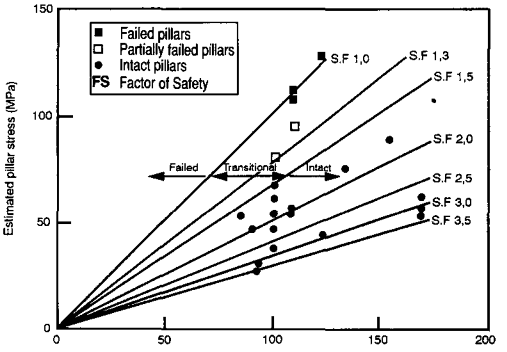


**Figure 5—Relationship between pillar factor of safety and pillar performance as obtained from Elliot Lake Quirke Mine[3]**

*Table I*

**A summary of non-yield pillar layouts used in hard-rock mines**

| | | | | IN PANEL PILLARS | | | | | | | BARRIER PILLARS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Dimensions | | | Spacing | | | | Dimensions | | Spacing | |
| Mine | Reef | Depth | Dip Angle | strike | dip | height | dip | strike | w/h (eff) | Areal e (in panel) | strike | dip | strike | dip |
| Impala | Merensky | < 160 | 9 | 3 | 3 | 1,1 | 32 | 30 | 2,7 | 0,99 | – | – | – | – |
| Impala | Merensky | ~ 200 | 9 | 5 | 5 | 1,1 | 32 | 30 | 4,5 | 0,97 | 10 | – | 200 | – |
| Impala | Merensky | ~ 500 | 9 | 5 | 5 | 1,1 | 32 | 30 | 4,5 | 0,97 | 20 | – | 400 | – |
| Impala | UG2 | ~ 300 | 9 | 5 | 5 | 0,9 | 22 | 16 | 5,6 | 0,97 | 10 | – | 200 | – |
| Impala | UG2 | > 500 | 9 | 6 | 4 | 0,9 | 32 | (2) | 5,3 | 0,91 | 20 | – | 400 | – |
| Western Plat | Merensky | < 300 | 11 | 4 | 20 | 1 | (2) | 34 | 6,7 | 0,89 | – | – | – | – |
| Western Plat | Merensky | ~ 500 | 11 | 5 | 20 | 1 | (2) | 36 | 8,0 | 0,87 | – | – | – | – |
| Western Plat | UG2 | < 300 | 11 | 4 | 20 | 1 | (2) | 34 | 6,7 | 0,89 | – | – | – | – |
| Western Plat | UG2 | ~ 500 | 11 | 5 | 20 | 1 | (2) | 36 | 8,0 | 0,87 | – | – | – | – |
| Western Plat | UG2 | ~ 800 | 11 | 6 | 20 | 1 | (2) | 36 | 9,2 | 0,85 | – | – | – | – |
| Atok | Merensky | < 450 | 20 | 3 | 2 | 0,9 | 30 | (2) | 3,5 | 0,96 | – | – | – | – |
| Lavino | LG6 | < 100 | 12 | 3 | 6 | 1,9 | (3) | 20 | 2,1 | 0,90 | – | – | – | – |
| Lavino | LG6 | > 100 | 12 | 5 | 5 | 1,9 | (6) | (6) | 2,6 | 0,79 | – | – | – | – |
| Winterveld | MG1 | < 70 | 12 | 3 | 3 | 1,1 | (10) | (10) | 2,7 | 0,95 | – | – | – | – |
| Winterveld | MG1 | > 500 | 12 | 4 | 4 | 1,1 | 26 | (2) | 3,6 | 0,90 | – | – | – | – |
| Winterveld | MG1 | > 500 | 12 | 6 | 6 | 1,1 | 34 | (2) | 5,5 | 0,87 | 10 | – | 180 | – |
| Dilokong | MG1 | < 350 | 14 | 10 | 6 | 1,1 | (32) | (2) | 6,8 | 0,87 | – | – | – | – |
| Dilokong | MG1 | < 350 | 14 | 6 | 2 | 1,1 | (32) | (2) | 2,7 | 0,96 | – | – | – | – |
| Dilokong | MG1 | > 350 | 14 | 10 | 7 | 1,1 | (14) | (2) | 7,5 | 0,72 | – | – | – | – |
| Otjihase | | ~ 300 | 7 | 10 | 5 | 5 | 10 | (2) | 1,3 | 0,58 | – | – | – | – |
| Wessel | | ~ 300 | 4 | 6 | 6 | 4 | (8) | (8) | 1,5 | 0,82 | – | – | – | – |
| Nchwaning | | > 300 | 4 | 7 | 7 | 3 | (8) | (8) | 2,3 | 0,78 | – | – | – | – |
| Gloria | | > 300 | 4 | 20 | 6 | 5 | (8) | (8) | 1,8 | 0,69 | – | – | – | – |
| Koretsi West | Crocidol. | ~ 160 | 4 | 2 | 2 | 1,9 | (6) | (6) | 1,1 | 0,94 | – | – | – | – |

Bracketed values of pillar spacing refer to skin-to-skin measurements, otherwise values are centre-to-centre measurements
Unit for dimensions is metres
Average values are used throughout

determined from back-analysis. In redesigning a hard-rock mine at an average depth of 130 m, Kersten found $K$ values averaging approximately one-third of the reef UCS, by using Wagner's perimeter rule for estimating the strength of rectangular pillars, assuming $\alpha = -0{,}75$ and $\beta = 0{,}5$. Kersten's method is simple and easy to use; however, there are certain simplifying assumptions, and there may be difficulties estimating the actual state of pillars from the degree of pillar spalling without quantifying the extent of fracturing into the pillar.

Table I gives a summary of the non-yield pillar layouts currently in use; they are individually discussed later in this paper.

### *Crush pillars*

As depth increases, extraction ratios associated with coal-type bord-and-pillar layouts become increasingly unfavourable. However, the increasing mining depth results in relatively smaller tensile zones, and this in turn permits the safe use of reduced levels of support resistance: the support no longer needs to carry the full weight of overburden, but rather only the weight of superincumbent strata reaching up to the furthest active weak parting in the hangingwall. Thus small $w/h$ ratio pillars ($w/h < 3$), which can provide the required reduced support resistance in their post-peak residual strength state, can be used. For example, to support the deadweight of as much as 35 m of immediate hangingwall strata, only 1 MPa of support resistance is required, and this is easily provided by the residual strength of a crushed relatively slender pillar. These types of pillars will be called *crush pillars;* they can be defined as pillars intended to 'crush' while they are still part of the face, but which have sufficient residual strength to provide the required support resistances to the immediate hangingwall, both at the face and in the back areas. These pillars can yield over a large deformation range at their residual strength level (e.g. point C in Figure 3).

The $w/h$ ratios for crush pillars are typically 1,7 to 2,5. Many mines exploiting Merensky Reef use crush pillars with strike dimensions of 2, 3, 4, or 6 m and dip dimensions of 2 or 3 m, separated by 0,5 to 3 m wide ventilation holings. These pillars are normally aligned on strike on the down-dip side of strike gullies, often with a 1 m siding.

*Table II*

**A summary of crush pillar layouts used in hard-rock mining**

| | | | | IN-PANEL PILLARS | | | | | | | BARRIER PILLARS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Dip | Dimensions | | | Spacing | | w/h | Areal e | Dimensions | | Spacing | |
| Mine | Reef | Depth | angle | strike | dip | height | dip | strike | (eff) | (in panel) | strike | dip | strike | dip |
| RPM (Rstbrg) | Merensky | 400 | 9 | 6 | 2 | 1,1 | 36 | (3) | 2,7 | 0,96 | – | – | – | – |
| RPM (Rstbrg) | Merensky | 650 | 9 | 4 | 2,5 | 1,1 | 36 | (4) | 2,8 | 0,97 | – | – | – | – |
| RPM (Rstbrg) | Merensky | 650 | 9 | 4 | 3 | 1,3 | 36 | (4) | 2,6 | 0,96 | – | – | – | – |
| RPM (Rstbrg) | UG2 | 400 | 9 | 3 | 3 | 1,1 | 25 | (3) | 2,7 | 0,94 | – | – | – | – |
| RPM (Union) | Merensky | 650 | 18 | 4 | 2 | 0,9 | 35 | (2) | 3,0 | 0,96 | – | – | – | – |
| RPM (Union) | Merensky | 1000 | 18 | 4 | 2 | 0,9 | 35 | (2) | 3,0 | 0,96 | – | – | – | – |
| RPM (Union) | Merensky | 200 | 18 | 4 | 2 | 1,3 | 35 | (2) | 2,1 | 0,96 | – | – | – | – |
| RPM (Union) | UG2 | 700 | 18 | 4 | 4 | 1,7 | 35 | (2) | 2,4 | 0,92 | – | – | – | – |
| RPM (Aman.) | Merensky | 400 | 9 | 3 | 4 | 1,3 | 36 | (2) | 2,6 | 0,93 | – | – | – | – |
| Randfontein | Elsburg | 700 | 20 | 9 | 2 | 1,2 | (32) | (2) | 2,7 | 0,95 | 20 | 60 | 170 | 140 |

Bracketed values of pillar spacing refer to skin-to-skin measurements, otherwise values are centre-to-centre measurements
Unit for dimensions is metres
Average values are used throughout

The design of crush-pillar layouts is most commonly carried out by initially using pillar dimensions which have been successful in similar geological situations elsewhere[8]. Depending on the performance of the new layouts, the pillar dimensions and spacing are adjusted until the pillars provide the required behaviour. Alternatively, the initial *w/h* ratio for design can be specified to be 2, and if pillars do not crush initially, the *w/h* ratio is decreased until stable crushing is achieved. The *w/h* ratio normally does not exceed 2,5, and should not be less than about 1,5 in narrow stope widths. In some cases, the failure mode of pillars guides the *w/h* ratio selection. Structural weaknesses, such as thin bands of soft material or a relatively weak foundation rock, can provide the 'crushing' mechanism[8].

Table II gives a summary of the crush-pillar layouts currently in use; they are individually discussed later.

### *Yield pillars*

The correct depth at which the transition from non-yield to crush-pillar systems should take place, is not immediately apparent and requires careful consideration. Ozbay and Roberts[9] defined a transition zone; where the pillar stresses are too high for non-yield pillars of reasonable size, and yet are too low to cause immediate fracturing at the face so that crush pillars can safely be formed in their residual strength state. This is a difficult situation where over-sizing of crush pillars could result in pillar bursting. In some cases, for example coal mines employing longwalls, small *w/h* ratio pillars can be designed to be intact initially but then are allowed to be loaded beyond their peak strength in a stable manner. Ideally, such pillars could be designed with a factor of safety (FS) of 1 so that the pillars can exert their maximum support to the hangingwall[10]. These pillars will be called *yield pillars;* they are defined as pillars which are intended to have an FS > 1 or even FS equal to 1 when first formed, but then to yield in a stable manner at stress levels near to peak strength (point *Y* in Figure 3). The *w/h* ratios are as low as 3 but often approach 5.

Yield pillars are initially intact but, as mining progresses, the stresses acting on them increase to the levels equivalent to their strength. Provided that the pillar's post-peak stiffness is less than the stiffness of the loading strata, these pillars can yield in a stable manner. Such stable post-peak behaviour is assured if the post-peak modulus is not negative, i.e. a horizontal or rising post-yield stress–strain behaviour.

At present, the design of hard-rock yield pillars is also largely empirical. Little is known of the fundamental behaviour of yield pillars, and inconsistencies are often evident between theory and practice. Theoretical studies indicate that the levels of regional or local stiffness do not favour stability for slender hard-rock pillars, yet preliminary observations indicate that stable load shedding of such pillars can take place at *w/h* ratios of less than 2,5[11, 12]. Also, it is thought that pillars with *w/h* ratios ≥ 5 cannot fail in an unstable manner, yet bursting of 5 x 5 m pillars in the back areas was reported[13]. These cases need to be rationally analysed using numerical and laboratory modelling, together with the collection of further *in situ* data.

Table III gives a summary of the yield-pillar layouts used in various hard-rock mines, which are discussed in further detail later.

*Table III*

**A summary of yield pillar layouts used in hard-rock mining**

| | | | | IN-PANEL PILLARS | | | | | | | BARRIER PILLARS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Dip | Dimensions | | | Spacing | | w/h | Areal e | Dimensions | | Spacing | |
| Mine | Reef | Depth | angle | strike | dip | height | dip | strike | (eff) | (in panel) | strike | dip | strike | dip |
| Impala | Merensky | 500 | 9 | 5 | 5 | 1,1 | 32 | 30 | 4,5 | 0,97 | 20 | – | 400 | – |
| Impala | UG2 | 500 | 9 | 6 | 3 | 1,1 | 32 | (2) | 3,6 | 0,93 | 20 | – | 400 | – |
| Impala | UG2 | 500 | 9 | 6 | 4 | 1,1 | 32 | (2) | 4,4 | 0,91 | 20 | – | 400 | – |
| Impala | Merensky | 800 | 9 | 6 | 3 | 1,1 | 32 | (2) | 3,6 | 0,93 | 20 | – | 400 | – |
| Impala | Merensky | 800 | 9 | 6 | 4 | 1,1 | 32 | (2) | 4,4 | 0,91 | 20 | – | 400 | – |
| Impala | UG2 | 900 | 9 | 6 | 3 | 0,9 | 32 | (2) | 4,4 | 0,93 | 20 | – | 400 | – |
| Impala | UG2 | 900 | 9 | 6 | 4 | 0,9 | 32 | (2) | 5,3 | 0,91 | 20 | – | 400 | – |
| RPM (Union) | UG2 | 300 | 18 | 5 | 5 | 1,7 | 36 | (2) | 2,9 | 0,90 | – | – | – | – |
| RPM (Aman.) | UG2 | 100 | 16 | 4 | 4 | 1,3 | 36 | (2) | 3,1 | 0,93 | – | – | – | – |
| DRD | Main | 1000 | 20 | 8 | 9 | 5 | (2) | (25) | 1,7 | 0,80 | 20 | – | (250) | – |
| Joel | Beatrix | 700 | 15 | 3 | 3 | 2 | (40) | (3) | 1,5 | 0,97 | 9 | 6 | 120 | 120 |
| Beatrix | Beatrix | 900 | 11 | 5 | 5 | 1,5 | (35) | (40) | 3,3 | 0,98 | – | – | – | – |
| Beatrix | Beatrix | 700 | 8 | 12 | 8 | 4,5 | (15) | (2) | 3,5 | 0,70 | – | – | – | – |
| Randfontein | Elsburg | 800 | 30 | 7 | 7 | 5 | (32) | (2) | 2,8 | 0,86 | 30 | 30 | (150) | (150) |

Bracketed values of pillar spacing refer to skin-to-skin measurements, otherwise values are centre-to-centre measurements
Unit for dimensions is metres
Average values are used throughout

*Barrier pillars*

Pillar layouts in shallow mines involving small in-panel pillars often include large $w/h$ ratio pillars, known as *barrier pillars* to provide regional stability to the entire mine. The important consideration in the design of regional pillars is their strength; they are designed to remain essentially elastic and intact over the entire life of the mine. According to Salamon[14] choice of squat pillars having $w/h$ ratios > 10, should ensure indestructibility of the barrier pillars, though the possibility of foundation failures (e.g. punching or footwall heave) needs to be checked in highly-stressed situations, or where hanging- or footwalls are relatively weak.

Barrier pillars are usually rib or rectangular in shape, and oriented on dip or strike. Where appropriate, unpayable areas (e.g. potholes, fault losses) may be incorporated into regional pillar layouts. However, it is very important that these pillars are not oriented parallel to geological weaknesses or joint sets in the rockmass, which could otherwise both weaken the regional pillars, and promote the possibility of large falls of ground in the stopes. It appears that there is uncertainty and diversity of opinion as to the need for, and design of barrier pillars. A wide range of designs, sizes, and spacings were encountered in the industry survey.

The main purposes of leaving barrier pillars are:

- to compartmentalize the mining into distinct regions, so that, if a collapse should occur in one region, it will be prevented from spreading into neighbouring stopes
- to reduce excessive closures and surface subsidences which would otherwise occur in panels supported only by crush pillars
- to assist in the control of the tensile zone and the prevention of surface subsidence
- to increase effective strata stiffness substantially so as to reduce the possibility of large-scale instabilities (pillar runs) in stopes supported by non-yield pillars.

The recently observed increase in seismicity levels on the deeper mines of the BIC, indicates that barrier pillars may also be required to restrict volumetric stope closures and corresponding seismic energy release potentials. The design of pillars for this purpose may differ from barrier pillars used at present, and will need detailed investigation.

Ryder and Ozbay[6] give the following summary of the criteria used in selecting the spacing of barrier pillars: a conservative rule of thumb sometimes used is to keep the span, $L$, less than about one-quarter of the depth, $H$, i.e. $H/L > 4$.

A number of theoretical results can be cited to support this rule.

Firstly, the height of the tensile zone is lower at $H/L = 4$ than it is at $H/L = 2$, thus reducing the burden placed on the in-stope yield or crush pillars for tensile-zone control.

Secondly, the hangingwall stiffness falls off fairly rapidly for $H/L <$ approximately 2, and this could prejudice the stability of certain in-stope non-yield pillar layouts.

Thirdly, in-stope closures and surface subsidences in a yielding-pillar layout increase in direct proportion to span, *L*, but are often at acceptable levels if *H/L* is approximately 4. In shallow non-yield pillar layouts, much lower *H/L* ratios may be acceptable since the in-stope pillars themselves provide substantial tensile-zone control. However, for adequate compartmentalization *L* should rarely exceed 250 m. Moreover, at low *H/L* ratios, adequate factors of safety, to prevent regional instability, become difficult or impossible to achieve, and this places an increased premium on the choice of an adequately high factor of safety for the strength of non-yield in-stope pillars.

The final choice of an operational regional pillar span, *L*, can be guided by numerical modelling, but this may well require modification and experimentation in practice, particularly in the light of local geological conditions encountered during mining.

## Pillar-design methods and current practice

Impala Platinum Mines initially used 3 x 3 m non-yield pillars, spaced 30 m on strike and 32 m on dip, at shallow depths. This system worked until the mining depth reached 160 m, at which depth a large collapse occurred. The pillar sizes were then increased to 5 x 5 m. These 5 x 5 m non-yield pillars are still being used in shallow operations on both Merensky and UG2 Reefs at depths of about 400 to 500 m. Pillars with *w/h* ratios ≥ 5 are currently believed to provide a positive post-peak slope, and can be safely loaded beyond their elastic limit. A typical example is the pillar layout used at Impala Platinum Mines, where 5 x 5 m pillars (in a chequer-board pattern of 2 pillars per 32 x 30 m) have been adequately supporting the hangingwall at depths of 500 m or greater, and are free from any sign of fracturing until they are about 30 m in the back area. The mode of yielding of these pillars is generally stable although occasional 'bumps' are said to occur in the back areas.

Numerous instrumented field experiments and pillar-design studies have been carried out at Impala over the past 20 years[13, 15–22]. These studies suggest that 5 x 5 m pillar properties vary widely, depending on geological factors such as the local density of jointing. Occasionally, pillars can fail through to the core at comparatively low stress levels. However, in most cases it would seem that 5 x 5m pillars are significantly stronger than once thought—under high stress the edges spall but the central core tends to remain intact. For example, Spencer[21] estimated an APS equal to 219 MPa for an elastic unfailed 5 x 5 m pillar in a UG2 stope at a depth of 588 m. This value was consistent with *in situ* stress measurements, whereas the strength estimate using formulae, accepted at that time, was only 85 MPa. An interesting observation was that the pillar was free of any fracturing only when it was first cut, and started fracturing as the face advanced away from the pillar. Petroscope observations showed that, within ten months, pillar-sidewall fracturing extended 0,4 m deep into the pillar. The remaining inner part of the pillar was unfractured. It is not impossible, therefore, that because of their strength, many of the 5 x 5 m pillars at Impala are not functioning as yield pillars at all, but are instead operating as conventional non-yield pillars. Large parts of the deeper areas of Impala are now being mined on more slender yield pillars (minimum *w/h* ratio of about 3). These appear to be functioning satisfactorily at present, although seismicity levels are occasionally a cause for concern.

At Impala, experience shows that open spans of more than 120 m cannot be achieved[20]. A system of barrier pillars is used in this mine at depths greater than 100 m. These comprise 20 m wide barrier pillars spaced to give depth/span ratios approximately 2[17]. At relatively deeper workings, the barrier pillars on the Merensky and UG2 workings are superimposed, and are spaced at about 400 m.

RPM Rustenburg Section started mining with total extraction of Merensky Reef in 1927. Initially the support consisted of stonewalls and timber props, and this proved satisfactory. The timber props showed no signs of deformation, implying low elastic convergence and a self-supporting hangingwall. As mining advanced deeper than 200 m, trials were carried out to replace stonewalls by stonepacks (stone-filled skeleton packs). Backbreaks were experienced with this system when the strike span reached 60 m. Lines of crush pillars spaced 45 m on dip were then introduced. The dip spacing of crush pillars was subsequently reduced to 36 m as backbreaks still occurred at the 45 m spacing. In 1974, longwall mining with crush pillars was introduced at the Frank Shaft area at a depth of 500 m. The layout in longwall mining is typically 2 to 2,5 m wide strike pillars with a dip spacing of 36 m. The pillars in the 19 longwall stope at Frank Shaft measure 6 m long, 2 m wide and 1 m high, separated by 2 m wide ventilation holings. The mechanism of stable crushing is explained[8] as the eventual crushing of large crystals in the yielding pyroxenite matrix. The pillar ends up as an intensely fractured but still well-knit mass of crushed rock. This pillar system has generally been successful in providing the required hangingwall support, although some pillars are said to be 'punching' or even 'bursting' 150 m behind the face on the Townlands longwall, due to abnormal amounts of strong norites or anorthosites in pillars affected by rolling-reef conditions. At present, RPM uses three different support systems, depending on the ground conditions

- grout packs (along gullies) and timber props (in stope)
- crush pillars (along gullies) and timber props (in stope)
- crush pillars (along gullies), grout packs and timber props (in stope).

No barrier pillars are being used at the RPM mines.

RPM Union Section mines deeper and wider Merensky Reef than that mined at the RPM Rustenburg Section. Initially, mining was carried out using 0,6 x 0,6 m mat packs at skin-to-skin distances of 3 m on dip and 2,4 m on strike. Spans could not be kept open beyond 30 to 40 m with this support system and crush pillars along strike gullies were introduced in 1977. These pillars measured 1,5 m wide and 3 m long with 1 m ventilation holings, and were spaced 35 m centre-to-centre along dip[23]. Backbreaks persisted and it was thought that the pillars were too slender.

The pillars were subsequently made squatter by changing their dimensions to 2 x 2 m with 2 m holings. The extent of crushing was less compared to 1,5 x 3 m pillars. Wood and Coetzer[24] reported that the performance of this pillar system had been satisfactory and that no further backbreaks had occurred. Current pillar dimensions are 4 x 2 m if sidings are used, or 4 x 3 m if pillars are cut immediately adjacent to gullies. No barrier or regional pillars have been employed in this mine. Bord stability remains the major problem as the hangingwall rock (Harzburgite) is heavily jointed in places, giving rise to plug-type failure along vertical planes adjacent to pillars.

Union Section has also been mining the UG2 Reef for the last 5 years. At about 35 m below the old Merensky workings, square pillars with side length of 5 m are being used to give 90 per cent areal extraction. At greater depths (~700 m) pillar side length is reduced to 4 m. Plug types of bord failure occur occasionally.

RPM Amandelbult Section initially employed 4 x 2 m strike pillars at 45 m dip centre-to-centre spacing. This system could not prevent collapses which extended up to the pyroxenite-norite transition, 2 m above the stope. The spacing was subsequently reduced to 36 m and pillar dimensions of 3 m long and 4 m wide were used successfully. The stoping width is relatively high, being about 1,3 m, and the average mining depth is about 400 m.

Western Platinum Mines previously used a layout comprising the development of dip centre gullies, 150 m apart, from which strike gullies were developed 40 m apart on dip. As mining proceeded away from the centre gullies, pillars were established on a line 2 m below the strike gullies. The dimensions of the pillars varied from 10 x 10 m to 2 x 6 m. When encountered, potholes were utilized to form pillars. Between the pillars 15 cm diameter timber props were placed at 2 x 2 m spacing. This system provided the required support system for hangingwall control. Presently, the Western Platinum Mine employs up-dip mining. Where possible, potholes (about 16 per cent of the reef) are incorporated as pillars. Nominally, dip-pillars are designed to be 20 x 5 m with a 2 m holing between pillars. The strike distance between pillars is 36 m. Without using barrier pillars, overall extraction ratios of about 89 per cent is being achieved. Hangingwall conditions are good, and high rates of face advance are achieved.

Lebowa Platinum (Atok Section) mines from near surface to a maximum depth of about 450 m. A uniform pillar design is used comprising 3 x 2 m pillars separated by ventilation holings at a dip spacing of 30 m centre-to-centre. The stope width is 0,8 to 0,9 m. The hangingwall-pyroxenite beam is only 0,15 m thick, and the Bastard Merensky parting is at 10 m in the hangingwall. No major falls have been reported; typical falls of ground are less than 0,5 m thick. No barrier pillars are used, apart from numerous unmined pothole blocks.

Lavino Chrome Mine initially used nominally 3 to 4 m wide 1,8 to 2,0 m high dip pillars at a strike distance (skin-to-skin) of 20 m, although the actual layout shows considerable variations in these dimensions. Scaling and various degrees of fracturing were observed in some of the pillars which had a width of less than 3 m at depths of about 100 m. The fracturing appeared to have been governed by the serpentinized bedding at the mid-height of the pillars. A shallow-dipping joint system parallel to the strike occasionally caused bord failures extending up to 1 m into the hangingwall. Also, larger falls, extending 4 to 5 m into the hangingwall, occurred between steep dipping joints. The current pillar layout is more conservative. It consists of 5 x 5 m pillars on 6 m bords both on strike and dip. A 20 m wide strike-orientated barrier pillar at a depth of 120 m, now separates the old workings from the current mining area. This system of pillars appears to have prevented pillar fracturing and bord failures. Currently, Lavino Chrome Mine is introducing 20 m wide strike-orientated barrier pillars.

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Winterveld Chrome Mine used 3 x 3 m pillars, with 10 m spacing both along strike and dip. Following a large collapse involving about 50 pillars which took place at 70 m below surface, pillar sizes were increased, and a system of strike pillars of alternating dimensions—8 x 8 m and 4 x 4 m—was introduced. This layout was later changed to 6 x 6 m pillars located along strike with ventilation holings of 2 m between them. The skin-to-skin dip spacings are 28 m. A system of barrier pillars was subsequently added to the layout, and comprises 10 m wide continuous dip pillars 180 m apart. At depths of about 500 m, no signs of visible scaling are apparent on the in-panel pillars except for occasional slight slabbing occurring at the up-dip corners of the pillars or intense curved fracturing at pillar mid-height. Winterveld is introducing 10 m wide dip-barrier pillars at depths greater than 500 m.

Randfontein Estates Gold Mine mines mainly the reefs in the Elsburg series. Depending on the distance between the individual reefs, the mining is carried out along either a single reef with stoping widths of 1 to 3 m, or multiple reefs with stoping widths of 5 to 8 m. Many pillar-system designs are used to cater for a large range of geotechnical conditions. At depths of about 700 m, in the areas where the stoping width varies from 1 to 3 m, the typical crush-pillar layout comprises 1,6 to 3 m wide and 9 m long strike pillars, separated by 2 m ventilation holings with a dip spacing of 32 m. Where possible, the *w/h* ratio of the crush pillars is kept at 1,65 as greater *w/h* ratio pillars are said to be burst-prone. Intermediate low-friction layers provide a stable crushing mechanism resulting from the enhanced vertical slabbing of the top and bottom portions of the pillar caused by the partings[8]. In the high stoping width areas, two different mining methods are employed. In the backfill sections, 7 m wide cuts are taken along the strike direction at 7 m intervals on dip. The mined-out area is subsequently backfilled, and the 7 m wide strike strip pillars between backfilled sections are mined. This method has generally proved successful. In the bord-and-pillar sections, the primary extraction is carried out in the same way as in the backfill sections, followed by a secondary extraction process of cutting 7 m wide slots through the strike pillars, creating individual square pillars measuring 7 x 7 m. Prior to secondary extraction, the pillars do not show any sign of slabbing or failure. Soon after secondary extraction, the pillars start fracturing. Occasional backbreaks and severe pillar-sidewall fracturing are observed in the bord-and-pillar sections. Computer simulations show that the average stress acting on these pillars is approximately 120 MPa[25]. Backbreaks were a common phenomenon in shallow sections of the workings at Randfontein Estates. They used to occur at spans between 100 and 250 m depending on local conditions. The incidence of backbreaks fell after the introduction of barrier pillars, but could only be reduced to insignificant levels after the introduction of crush-pillar systems. Regional pillars are 20 m wide (strike) and 60 m long (dip), spaced 170 m and 140 m on strike and dip, respectively. In the newer areas, the barrier-pillar size and spacing are 30 x 30 m and 150 m, respectively.

Joel Gold Mine uses 3 m square pillars located along the up-dip side of the gully and separated by 3 m holings at depths of 500 m. The dip-centre spacing of the pillars is about 40 m. The yielding mechanism of the in-panel pillars is in the form of stable punching of the pillars into the footwall, which results in some footwall heave in the back-areas, but is otherwise satisfactory. The mine has introduced 6 x 9 m regional pillars on a 120 x 120 m grid.

Beatrix mines at depths of about 800 to 1000 m. The mining height varies from 0,9 to 6 m. In the low stoping-width areas (0,9 to 2 m), the layout comprises 5 x 5 m pillars with centres separated 40 m on strike and 35 m on dip. In the high stoping-width areas (3 to 6 m), nominally 8 m wide strike, rib pillars are left at a dip spacing of 15 m. The mode of yielding is stable punching of pillars into hanging- and footwalls. No barrier pillars are employed.

Durban Roodepoort Deep (DRD) currently mines Main Reef at depths of 800 to 1000 m. Pillars were introduced in 1987 to prevent local hangingwall collapses in high stope width areas (> 2 m). Initially pillars with *w/h* ratio equal to 2 were used but these remained uncrushed at considerable spans. The pillar dimensions were changed to *w/h* is equal to 1,7, and observations indicated that the pillars were yielding in a stable manner 20 to 30 m behind the face. At present, rib pillars located along dip with 2 m ventilation holings, are being employed. Grout packs are installed on both sides of the pillars, owing to high gully sides. The skin-to-skin open span along the strike direction is 25 m, and barrier pillars are left at a spacing of approximately 250 m[11]. Durban Roodepoort Deep has introduced barrier pillars at a spacing of 250 m.

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Manganese Mines (Wessels, Nchwaning and Gloria), in general, employ the bord-and-pillar method of mining, using 8 m wide bords and 6 to 20 m wide square pillars in 2 to 8 m high stopes. The *w/h* ratios are mostly in the order of 1 to 1,5. At typical depths of around 300 m, the pillars do not show any sign of fracturing or slabbing. In some cases, bord stability causes some concern, and the roof stability in these cases is ensured by employing 2,4 m long roof bolts with 1,5 m spacing in the well-laminated and jointed-banded ironstone hangingwall where this is exposed. No barrier pillars are used.

Koretsi West Asbestos Mine extracts crocidolite asbestos from a horizon where economic concentrations of fibre seams occur over a stoping width of 1,8 to 2,0 m. Mining takes place at a depth of approximately 160 m, and the strata dip westward at 3 to 4 degrees. The hanging- and footwall strata comprise well-laminated banded ironstones. Bord-and-pillar mining is practised with 2 x 2 m pillars and 6 m bords, resulting in 94 per cent extraction. The banded ironstone roof is very laminated, and is supported by 1,2 m roofbolts on a 1,2 x 1,2 m grid. The pillars show no signs of failure, and the pillar system appears to be totally adequate to provide overall stability to the mine, particularly when considering that ore bodies in the area are generally small, often measuring less than 500 by 500 m.

## Non-yield pillars—Collapsed cases

Non-yield pillar layouts carry the risk of a pillar run, which is a sudden collapse of pillars over large areas, often associated with seismicity, subsidence, and airblast. Some of the non-yield pillar-layout collapses are summarized in Table IV and briefly reviewed.

**Impala Platinum.** The introduction of pillars at the Impala Mines came after a major collapse at a depth of 40 m. In spite of the shallow depth of the stopes, no surface subsidence was observed, and it was estimated that the collapse extended only up to 9 m above the Bastard Merensky Reef. Pillars with dimensions 3 x 3 m and located 32 m on dip and 30 m on strike, were then introduced. This system worked until mining reached a depth of 160 m, where a massive collapse over an area of 600 x 900 m occurred, and surface subsidence was observed[17]. Soon thereafter, another collapse measuring 350 x 450 m at 50 m below surface took place in a neighbouring mine which was also using 3 x 3 m pillars. Assuming that the extraction ratio was

$$e = 1 - \frac{9}{32 \times 30} = 0,99 \qquad [4]$$

and a rock density of 2900 kg/m$^3$ applies for the overburden strata, the APS levels acting on the pillars prior to the failure can be estimated to have been 490 MPa at 160 m depth and 150 MPa at 50 m depth (using the formula $A = q/(1\text{-}e)$ where $A$ is the APS). In reality, the stress levels which caused failure should be somewhat less than these values since, as stated before, the above formula ignores the irregularities of the layout geometry and the presence of potholes.

**Lorraine Iron Ore Mine.** Tincelin and Sinou[26] reported on the nature of the sudden pillar collapses in the Lorraine Iron Ore Mine in France. Seven sudden collapses took place in this mine, all resulting in seismicity, with two of them causing fatalities. Bord-and-pillar mining was used for the extraction of a 5 m thick flat-lying reef at a depth of 140 m. Wide (12 to 15 m) square pillars, with 5 m skin-to-skin distance were employed, giving extraction ratios of about 60 to 70 per cent. The characteristics common to all seven cases were identified as:

*Table IV*

**A summary of collapsed cases of non-yield pillar layouts used in hard-rock mines**

| Mine | Reef | Depth | Barrier spacing | Dip angle | IN-PANEL PILLARS Dimensions strike | dip | height | Spacing dip | strike | w/h (eff) | Areal e (in panel) | Collapsed area, m$^2$ | Collapsed height, m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Impala | Merensky | 160 | N/A | 9 | 3 | 3 | 1,1 | 32 | 30 | 2,7 | 0,99 | 600 x 900 | |
| Impala | Merensky | 50 | N/A | 9 | 3 | 3 | 1,1 | 32 | 30 | 2,7 | 0,99 | 350 x 450 | |
| Lorraine | (France) | 140 | 140 | 0 | 15 | 15 | 5 | (20) | (20) | 3,0 | 0,82 | | |
| Otjihase | | 200 | N/A | 7 | 7 | 7 | 5 | (12) | (14) | 1,4 | 0,88 | 800 x ? | |
| Winterveld | MG2 | 70 | N/A | 10 | 3 | 3 | 1 | (10) | (10) | 3,0 | 0,95 | 45 x 100 | 10 |
| Quirke | (Elliot Lake) | 450 | N/A | 0 | 4,5 | 12 | 3 | (2) | (15) | 2,2 | 0,80 | 500 x 300 | |
| Lavino | LG6 | | N/A | 12 | | | 1,9 | | | | | | |
| Pomfret | Crocidolite | | N/A | 4 | | | | | | | | | |

Bracketed values of pillar spacing refer to skin-to-skin measurements, otherwise values are centre-to-centre measurements
Unit for dimensions is metres
Average values are used throughout

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- the immediate hangingwall was firm and sound
- the *w/h* ratio of pillars was 3 or less
- the collapses were sudden, and associated with seismicity, surface subsidence, and air blast.

It is important to note that these characteristics are similar to those of the Coalbrook disaster of 1962, where an area of 2,5 km$^2$ supported by 4400 pillars collapsed in 20 minutes. In both of these cases of sudden collapse, very little prior warning was noticeable in terms of pillar slabbing or hangingwall-fracturing.

**Otjihase Copper Mine.** The mine experienced a large collapse while mining operations were taking place at depths of 200 m. A system of primary and secondary extraction of the 3 to 10 m thick orebody was being used. Initially, the primary extraction was carried out using 7 m wide strike pillars to give 60 per cent extraction, followed by a secondary extraction process of cutting 14 m wide slots through the strike pillars, creating individual square pillars measuring 7 × 7 m, and resulting in 88 per cent final extraction. The collapse extended over a strike length of about 800 m within two days. Indications were that the failure commenced at the corners of pillars, and extended into the hanging- and footwall. This can be interpreted as foundation failure, which might have reduced the effective *w/h* ratio of the already slender pillars (*w/h* equal to 1,7).

**Winterveld.** Korf[23] and Ortlepp[27] reported a pillar collapse in the Winterveld Chrome Mine at 70 m below surface. The lateral extent of the collapse was 45 × 100 m, involving some 50 pillars. The height of the collapse into the hangingwall was estimated to be 10 m. The pillars in this case were designed to carry the load imposed on them by only the 10 m of hangingwall rock up to the major parting. In his discussion, Ortlepp emphasized that the behaviour of pillars would not be determined only by the 10 m height of the hangingwall, but by the elastic stope convergence, which was, in turn, determined by the regional geometry, and the height of the entire superincumbent strata.

**Quirke Uranium Mine**[28]. The mines stratified conglomerates, and uses rib pillars of 3 to 6 m width located along dip. The mining height varies from 3 to 6 m, and pillar *w/h* ratios from 0,7 to 1,5. On-reef haulages are located at 76 m intervals on down-dip, and are protected by strike-rib pillars of the same dimensions as the in-stope pillars. The bord widths employed vary from 15 to 20 m. In 1981, the Quirke Mine experienced a large sudden collapse in a flat-dipping section of the reef, covering an area of about 500 m on strike and 300 m on dip. The mining depth was 450 m, and the extraction ratio was, as quoted, about 70 to 85 per cent. The pillar failures were noted to be initially gradual and subsequently sudden, involving bursting of stope pillars. No barrier pillars were present in the collapsed area.

**Pomfret Asbestos Mine** and **Lavino Chrome Mine.** Both mines experienced collapses of large areas supported on slender pillars about 20 years ago. Further details of these collapse cases have not been obtained.

## Discussion

In summary, it would appear that pillar systems in use in South African hard-rock mines are, for the most part, performing satisfactorily. It is apparent, nevertheless, that current pillar-design methods are largely empirically based, and that often very different layouts are being used in neighbouring mines or in mines with similar geometries. It is entirely possible therefore, that some current layouts fall far short of being optimal in respect of (i) real safety, (ii) maximum safe extraction percentages, or (iii) flexibility in accommodating future mining scenarios in deeper or otherwise different geological conditions.

In broad terms, the merits and demerits of the pillar systems currently in use can be summarized as follows.

- Non-yield pillars in shallow operations, when properly implemented perform well; they maintain safety, and limit mining-induced disturbances to a minimum at relatively minor costs. However, they are, at present, difficult to design rationally, and therefore carry with them the risk of conceivably major mining disasters (pillar runs, heavy backbreaks), or alternatively, that of wasteful extraction percentages.
- Similar remarks apply, with even greater force, to yield-pillar layouts; which nevertheless at intermediate depths, provide the potential for giving increased extraction percentages while maintaining safe conditions.
- Crush-pillar systems seem, in practice, to be much easier to design, and provide high extraction percentages with adequate backbreak prevention and regional support in intermediate depth conditions. Their main possible drawback would seem to be that they allow greater mining disturbances (stope closures, surface subsidence, and face-stress concentrations) to take place when compared with non-yielding or yield-pillar layouts.
- Barrier pillars provide a final very robust line of defence against potential major mining disasters such as large pillar runs or regional backbreaks. However, they are not universally used, and procedures for their rational design are poorly defined at present.

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The pillar layouts discussed in this report may not readily provide solutions to some of the problems which will probably be experienced as mining depths increase. The experience gained from deep gold mining will undoubtedly be called upon for designing deeper mine layouts in the BIC, and elsewhere. However, the high $k$ ratios (typically $k > 1$), and highly jointed and serpentinized nature of the BIC rockmass, may bring about different mining conditions from those encountered in typical deep gold mines, which will require further fundamental and applied research.

Strategies against seismicity related problems need to be identified as soon as the seismic monitoring programmes, currently being carried out, indicate increased seismicity levels at relatively deeper parts of the BIC. Whether to use barrier (stabilizing) pillars or backfill, or a combination of the two, and when and how the transition from pillar to non-pillar mining can be adopted, needs to be investigated. As an alternative to the commonly used deep-level mining methods, consideration should also be given to pillar mining at great depths as a logical extension of the current methods. For example, a 75 per cent extraction using pillars with $w/h$ ratios of 7 or more, or by using crush pillars at depth may be acceptable as rock engineering strategies, provided that these methods are well understood, practical from a mining point of view, and economical.

## Conclusions

- The methods and design criteria for pillar mining have evolved from practical experience. These empirical methods do not always accommodate the differing rock properties, variability in rockmass conditions, and stress states encountered in the BIC and other base metal provinces.
- The most commonly used hard-rock pillar-strength formula

  $$\sigma_s = K\, h^{-0,75}\, w^{0,5} \qquad [5]$$

  is similar to Salamon and Munro's formula[1], but the parameters appear to be based on Elliot Lake Mine experience, which has different rock types, and where pillar $w/h$ ratios range only from 0,7 to 1,5. Based on very limited current evidence, it is possible that, at least for some BIC rock types, the relative strength of squat pillars versus slender pillars may be considerably understated by this formula.
- Generally in the BIC, 35 m bord widths are stable under relatively good hangingwall conditions. However, bord stability is difficult to achieve where the hangingwall rockmass is weak, laminated or severely jointed and, under these conditions, severely reduced bord widths seem to achieve adequate stability.
- Non-yield pillar layouts carry the risk of a pillar run, which is a sudden collapse of many pillars over a large area with extensive hangingwall failure, and is often associated with seismicity, subsidence, and airblast. The pillar-run cases in hard-rock mining, have similarities with regard to failure modes, and it is interesting to note that most sudden collapse cases took place at relatively shallow depths, i.e. 150 m or less. Again, methods and procedures for adequately determining pillar strengths and stresses are needed to ensure that pillar runs do not occur in non-yield pillar layouts.
- Based on current theory, low $w/h$ ratios for hard rock pillars ($w/h < 5$) are likely to fail in an unstable manner, yet stable failure of these pillars has been observed in some cases. Conversely, pillars having $w/h \geq 5$ should fail in a stable manner, yet cases of bursting have been noted. Further theoretical, laboratory, and *in situ* studies would lead to a better understanding of the mechanisms governing stable or unstable pillar-failure modes.
- A few direct attempts have been made to assess the numerical value of the residual strength of pillars. A rule-of-thumb used in shallow mining, based partly on *in situ* observations, is that a mature 2:1 yield pillar has a residual strength of at least 5 to 10 per cent of its peak strength. It is most likely, for example, that very different figures might apply for different rock types, and for varying $w/h$ ratios involved. Laboratory testing, numerical modelling, and *in situ* monitoring studies are needed to develop and generalize the current empirical design procedures.
- Although barrier pillars do not exhibit stability problems, the variations in their size and spacing in different mines (e.g. RPM does not use barrier pillars) indicate a need for improved understanding of the role of barrier pillars in affecting the stability of tabular pillar workings. Increasing levels of seismicity bring about the question of whether stabilizing pillars should be used for energy-release rate control in future deep-mining conditions in the BIC. ◆