THE ROLE OF OVERBURDEN INTEGRITY IN PILLAR FAILURE

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ABSTRACT

The move toward partial pillar extraction versus full pillar extraction has necessitated a new approach to underground section stability. When pillars are mined too small to support the weight of the overburden, they will, in some cases, remain stable for a considerable period; in other cases, they will collapse unexpectedly and violently. There is no discernable difference between the pillar safety factors of the failed and stable cases. The explanation lies in the characteristics of the overburden layers.

A method is proposed that recognizes the overburden characteristics in the evaluation of stability. Two stability factors are calculated: one for the pillars, the other for the overburden. Using this method, it is possible to make use of the bridging capabilities of overburden layers to prevent pillar collapse. It is possible to scientifically design partial pillar extraction layouts that will be safe. Using energy considerations, it is also possible to prevent violent failure of pillars.

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INTRODUCTION

In order for underground coal pillars to fail completely, two requirements must be met: (1) the pillars themselves must be loaded to beyond their load-bearing capacity, and (2) the overburden must deflect sufficiently to totally deform the pillars. In the consideration of pillar failure, the first requirement historically has received almost all of the attention; only scant mention is sometimes made of the role of the overburden.

Until recently, this has not been necessary. South African mining methods, longwalling apart, were either bord-and-pillar or pillar extraction methods with a number of variations. For bord-and-pillar, the pillars are sufficiently large to support the full weight of the overburden and the stiffness of the overburden is a bonus, merely decreasing the load on the pillars. In pillar extraction, the overburden usually fails completely, although there are situations where it is prone to be self-supporting for large enough distances to result in overloaded pillars and the well-known and understood negative consequences thereof.

Lately, however, there has been a move toward partial pillar extraction with a number of different names attached to the methods, like pillar robbing, pillar splitting, checkerboard extraction, etc. These methods all have in common the partial extraction of pillars, leaving self-supporting snooks (stubs) in the back area. They are usually larger than the ones left in normal stooping operations. These snooks are often stable for long periods of time, even though their strengths are less than that required to support the full overburden. This in turn creates the impression that the pillars are much stronger than the prediction made with the strength formula.

There have also been occasions where the snooks failed after a period of time. The author has been involved in investigations into two of these. In both instances, the lack of serious accidents can only be ascribed to luck, both having occurred in the off-shift. In one case, ventilation stoppings were destroyed for a distance of several kilometers; in the other, the collapse overran unmined pillars and resulted in severe roof falls up to six lines of pillars beyond the end of the split pillars.

The difference between the cases that failed and those that remained stable is not to be found in the strengths of the pillars. The range of safety factors was from 0.5 to 0.7, and the stable ones were not the ones with the higher safety factors. The pillar safety factor alone does not explain stability in these marginal cases. There were, however, significant differences in the overburden composition and stability. The investigation indicated that in the stable cases, the overburden was strong enough to bridge the panels; in the failed cases, the overburdens failed. This resulted in the development of a concept that takes into account the overburden stability as well as pillar stability. This concept will be explained in this paper.

EFFECTS OF MINING ON THE OVERBURDEN

Mining results in increased loads on the unmined pillars. This causes the pillars to compress; the amount of compression is a function of the additional load on the pillars and the pillar's modulus of elasticity. The pillar compression is translated into deflection for the overburden. The higher the pillar loads, the greater the compression and the more the overburden will deflect. In the most simplistic view, coal mine overburdens can be regarded as a series of plates that can be conveniently simplified further to a series of beams in the general case where the panel lengths are several times greater than the panel widths.

The beam deflection results in induced tensile stress in the upper beam edges and the bottom center of the beam. The most simplistic view, adopted here as the starting point for the development of a more accurate model, is that the beam will fail when the induced tension exceeds the sum of the virgin horizontal stress and the tensile strength of the beam material. However, it is well known that the overburden, consisting predominantly of sedimentary rock types often supplemented by a dolerite sill, is vertically jointed and therefore the tensile strength of the material can be ignored. Failure will thus occur when the induced tensile stress exceeds the virgin horizontal compressive stress.

The amount of deflection of any individual beam in the overburden is enhanced by the weight of the material on top of it and restricted by the resistance of the pillars underneath. There are no major differences in the moduli of the overburden rocks, dolerite sills apart, and the differential amounts of bending become a function of the thicknesses of the beams. In considering overburden stability, the identification of thick lithological units therefore is more important than the ratio of mining depth to panel width.

MATHEMATICAL RELATIONSHIP BETWEEN PILLAR LOAD AND OVERBURDEN DEFLECTION

The link between overburden deflection and pillar load is the pillar compression. The pillar cannot compress by a greater amount than the overburden deflection and vice versa. The maximum pillar deflection, Δh, is

$$\Delta h = \frac{\Delta \sigma}{E_c} h \,, \tag{1}$$

where h = pillar height,

$\Delta\sigma$ = load increase caused by mining,

and E_c = modulus of elasticity of coal.

The above is valid for the situation where the overburden is sufficiently soft not to restrict the compression of the pillars. There is general consensus that the modulus of elasticity of coal is around 4 GPa. However, the postfailure modulus is a function of the pillar shape. According to data supplied by van Heerden [1975], the postfailure modulus, E_{cf}, appears to be[2]

$$E_{cf} = \frac{0.562w}{h} - 2.293 \,. \tag{2}$$

Assuming tributary area loading conditions, the load increase on the pillars due to mining is

$$\Delta \sigma_p = \gamma H \left(\frac{1}{1 - e} - 1 \right) , \tag{3}$$

where H = mining depth,

e = areal extraction ratio,

and γ = ρg.

RELATIONSHIP BETWEEN PILLAR DEFLECTION AND INDUCED TENSION IN OVERBURDEN BEAM

The generic equation for beam deflection is

$$\eta = \frac{\gamma_r L^4}{32 E_r t^3} \,, \tag{4}$$

where L = panel width,

E_r = modulus of elasticity of the rock layer,

t = thickness of the rock layer,

and γ_r = unit load on the rock layer.

The generic expression for the maximum generated tensile stress is

$$\sigma_t = \frac{\gamma_r L^2}{2t^2} \,. \tag{5}$$

By substituting η by Δh, the tension induced by bending can also be expressed in terms of the deflection, as follows:

$$\sigma_t = \frac{16 t \Delta h E_r}{L^2} \tag{6}$$

This is the tensile stress that will be generated in the overburden beam if the restriction to deflection is the resistance offered by the pillars underneath. It is also the upper limit of the generated tension because the resistance offered by the pillars will not allow further deflection. However, the overburden has inherent stiffness that will also restrict deflection. The maximum deflection that an unsupported beam will undergo is indicated by equation 4.

If η from equation 4 is greater than Δh from equation 1, it means that the overburden is dependent on the pillars to restrict deflection and that the tensile stress generated in the beam is that found with equation 6. If Δh is greater than η, it means that the beam is sufficiently stiff to control its own deflection and that the tension generated in the beam is that found with equation 5.

[2] Author's own linear fit to van Heerden's data.

OVERBURDEN FAILURE

The overburden beams will fail if the induced tension exceeds the virgin horizontal compression; this is conveniently expressed in terms of the vertical stress as

$$\sigma_h = k\sigma_v, \tag{7}$$

or

$$\sigma_h = k\gamma H', \tag{8}$$

where H' is the depth at which the rock layer under consideration is located, not the depth of mining.

Next, define the overburden stability ratio (OSR) as

$$OSR = \frac{\sigma_h}{\sigma_t}. \tag{9}$$

PILLAR STABILITY

Pillar stability is evaluated by comparing pillar strength to pillar load; thus:

$$PSF = \frac{Strength}{Load} \tag{10}$$

The pillar load is conservatively estimated from the tributary area loading assumption as follows:

$$Load = \frac{\rho g H}{1-e}, \tag{11}$$

and the strength for South African pillars is [van der Merwe 1999]:

$$Strength = 4\frac{w^{0.81}}{h^{0.76}}. \tag{12}$$

OVERALL STABILITY EVALUATION

To evaluate the overall stability of a coal mine panel, it is necessary to consider both the overburden and the pillar stability. This can be done by viewing the two stability parameters—the pillar safety factor (PSF) and the overburden stability ratio (OSR)—separately, or better, by plotting the two onto a plane. The concept is illustrated in figure 1.

The quadrants in figure 1 have different meanings for the stability evaluation. In quadrant I, both the overburden and the pillars are stable. This is the ideal situation for main development.

In quadrant II, the overburden is stable, although the pillars are unable to support the full weight of the overburden. This is potentially the most dangerous situation because there could be a false impression of stability when the OSR is not much greater than 1.0. The pillars will be stable for as long as the overburden remains intact; however, the moment that the overburden fails, the pillars will also fail. This may occur because of time-related strength decay of the stressed overburden or when mining progresses into an area with an unfavorably oriented unseen joint set in the overburden. The closer the OSR is to 1.0, the more dangerous the situation.

Quadrant III indicates a situation where both the pillars and the overburden will fail. This is again the ideal situation for the snooks in pillar extraction. One wants both to fail in this situation.

Quadrant IV indicates that the pillars are able to support the overburden, even though the overburden may fail. This is also a safe situation, although gradual failure may occur over a long period as the pillars lose strength.

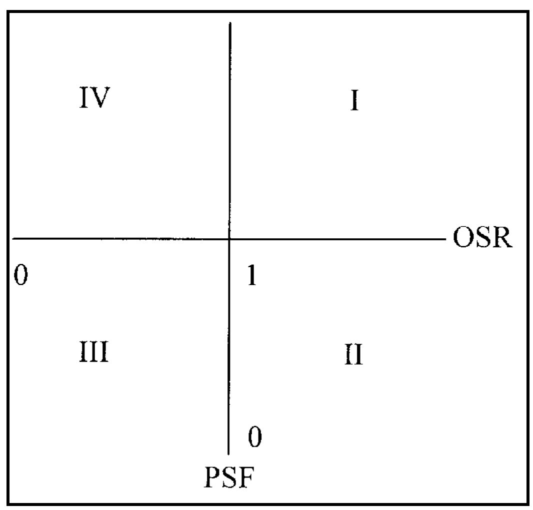

Figure 1.—Plot of OSR and PSF. Values of <1.0 for either indicate imminent instability.

PRACTICAL EXAMPLE

The following practical example is provided to indicate how the OSR/PSF procedure is applied in practice.

The mining depth is 143 m. The overburden consists of alternating layers of sandstones and shales. From the surface down, their thicknesses are as follows: 10, 5, 10, 20, 10, 50, 10, 10, 5, and 10 m. The mining height is 3 m; pillars are initially 18 m wide, and the roads are 6 m wide. The k-ratio is 2.0. The PSF is then 2.7, shown as point A in figure 2.

Pillars are then split by a 6-m-wide cut through the center, leaving remnants of 18 by 6 m, with an equivalent width (see Wagner [1980]) of 8 m. One line of pillars is left intact on either side of the panel, resulting in a width over which the pillars are split of 102 m. The PSF now decreases to 0.8. The OSR is calculated for each of the strata layers individually (see results in table 1).

It is seen from table 1 that because the pillars are beyond their failure limit, the overburden behavior is governed by the beam characteristics. Except for unit 6, all of the units will fail. Unit 6, however, is close to not failing and will probably be self-supporting for a short while. This combination of OSR and PSF is indicated by point B in figure 2.

During the time when they have not yet failed, it is probable that the pillars will have a stable visual appearance. Load cannot be seen. One's perception of pillar load is determined by the observed effects that accompany pillar compression, like slabbing. In this case, the pillar compression will be the greater of the deflection of unit 6 or the compression caused by the weight of the rock layers underneath unit 6. The deflection of unit 6 is 4 mm, and the compression of the pillars due to the weight of the strata underneath unit 6 is less than 2 mm. With the 4-mm compression of the pillars, the strain is 0.0013, which corresponds to a pillar load of 5.3 MPa. The strength of the snook is 8.4 MPa; the apparent safety factor is 1.6, and it will have the visual appearance of a stable pillar. However, the situation will change dramatically as soon as the overburden fails. At that moment, the pillars will be loaded by the full overburden weight. The safety factor will immediately decrease to 0.8.

Table 1.—OSR for the different strata layers with split pillars, panel width of 102 m

Unit No.	Thickness, m	0	)h	OSR
1	10	0.028	31.5	0.038
2	5	0.564	31.5	0.01
3	10	0.113	31.5	0.038
4	20	0.025	31.5	0.154
5	10	0.282	31.5	0.038
6	50	0.004	31.5	0.961
7	10	0.62	31.5	0.038
8	10	0.677	31.5	0.038
9	5	5.75	31.5	0.01
10	10	0.761	31.5	0.038

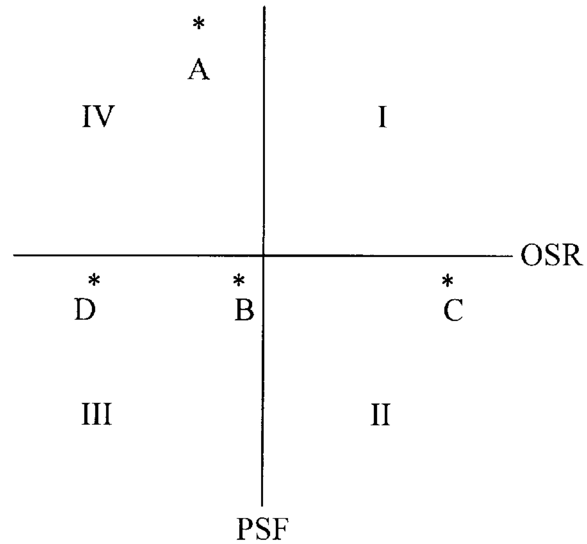

Figure 2.—OSR/PSF plot of the different options discussed in the example.

MODE OF FAILURE

Energy considerations indicate that failure will be violent if the stiffness of the pillars is less than that of the loading mechanism, which is the overburden. When the overburden fails, it loses continuity and, consequently, all stiffness as well. The stiffness of the loading mechanism is then 0. Therefore, the only way in which failure can be nonviolent in the situation where the overburden fails is where the pillars have a positive postfailure modulus. According to equation 2, this happens when the width-to-height (w/h) ratio of the pillars exceeds 4.08.

The w/h ratio of the pillars in this case is only 2.3; consequently, the failure will be violent, similar to what has been experienced on more than one occasion. This is similar to a conclusion reached by Chase et al. [1994], who analyzed pillar failures in the United States and found that massive collapses occurred where the w/h ratios of the pillars were less than 3. They also concluded that those collapses occurred where the overburden was able to bridge the excavation for a considerable distance before failure occurred.

The postfailure stiffness of coal with increasing w/h ratio of the pillars increases approximately linearly. There is thus no sudden distinction between what could be termed "violent" and "nonviolent" failure; rather, the relative degree of violence decreases with increasing w/h. It is suggested that the degree of violence be indicated by an index based on the magnitude of the postfailure stiffness of the coal, E_{cf}. It could be defined as follows:

$$I_v = 1 - \frac{E_{cf}}{4} \qquad (13)$$

With the limited information at hand, mainly that of Chase et al. [1994], it appears that if $I_v > 1.15$, the failure may result in a dangerous situation. This obviously also depends on the area involved.

By substituting equation 2 into equation 13, the relative degree of violence may be expressed in terms of the w/h ratio as follows:

$$I_v = 1.57 - 0.14\ w/h \qquad (14)$$

CONTROL MEASURES

There are a number of ways in which pillar splitting situations can be controlled using the OSR/PSF. One is to limit the width over which the pillars are split. For instance, if the width in the example is limited to 78 m (i.e., by splitting only three lines of pillars), the OSR of unit 6 increases to 1.6 and there is a much higher probability that the unit will remain to be self-supporting, if only for a longer time. Note that when this is done, the PSF is not affected; it remains at a value of 0.8. This situation is indicated by point C in figure 2. This corresponds to other situations that have been observed, i.e., where split pillars with low apparent safety factors remain stable for considerable periods of time.

A second alternative is to do full extraction of every second pillar on a checkerboard pattern, leaving the alternating pillars intact. When this is done, the PSF decreases to 0.7. The OSR of the strongest unit, No. 6, is 0.3, indicating failure of the overburden. This is shown as point D in figure 2. However, the w/h ratio of the pillars is 6.0, which means that the pillars will not fail violently. The attraction of this option is that 50% of all of the coal contained in pillars is extracted, as opposed to 17% using the method in the previous paragraph.

INFLUENCE OF GEOLOGY

A cautionary note must be expressed at this point. The process of pillar failure for low safety factor pillars is driven by the overburden characteristics. It is thus very important to have detailed knowledge of the overburden composition. For instance, if the thickness of unit 6 in the example is 40 m instead of 50 m, then the control measure to restrict the number of pillars to be split to 78 m will not be effective; the OSR in that case will be 1.0, which places it back into the category with the highest uncertainty. The example in the previous section is nothing more than an example to illustrate the application of the method: it is not to be viewed as a guideline for panel widths, etc.

The full application of the method will require the establishment of guidelines for limit values of OSR and PSF. It seems reasonable to assume that there will be an area in the center of the plot shown in figure 1 that is to be avoided—the area of highest uncertainty, where the values of OSR and PSF are close to 1.0. Those limits need to be established; the best way of doing that will probably be through back-analysis in areas where there are examples of failed and stable cases for different periods of time.

CONCLUSIONS

• For underground workings to collapse, both the pillars and the overburden must fail. The model described here, simplified as it is, offers a method to evaluate the stability of pillar workings with low pillar safety factors by adding an evaluation of overburden stability to the evaluation of pillar stability.

• Even if the pillars are not strong enough to support the overburden, it is possible to prevent collapse by limiting the panel width, thereby allowing the overburden to be self-supporting.

• Refinement of the model will enable the scientific design of alternatives to full pillar extraction, avoiding the situation where apparent stability caused by temporary bridging of the overburden leads to a false sense of security, only to be followed by catastrophic collapse.

• Quantification of the energy considerations can be done, leading to a design that will result in nonviolent failure of pillars.

• These conclusions are broadly similar to those reached by Chase et al. [1994]. The main difference is that this work offers a simple method of classifying the likelihood of failure occurring and the mode of failure should it occur.

ACKNOWLEDGMENTS

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REFERENCES

Chase FE, Zipf RK Jr., Mark C [1994]. The massive collapse of coal pillars: case histories from the United States. In: Peng SS, ed. Proceedings of the 13th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 69-80.

Van der Merwe JN [1999]. New strength formula for coal pillars in South Africa. In: Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 99-114, IC 9448.

Van Heerden WL [1975]. In situ determination of complete stress-strain characteristics of large coal specimens. J S Afr Inst Min Metall *75*(8):207-217.

Wagner H [1980]. Pillar design in coal mines. J S Afr Inst Min Metall *80*:37-45.