Current South African coal pillar research

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Synopsis

Over 206 million tons of hard coal were mined in South African collieries in 1996. Some 132.5 millions tons came from underground operations and approximately 120 million tons came from bord-and-pillar workings resulting in between 100 000 and 150 000 pillars being formed.

Coal pillar design remains a significant feature of South African mining. This paper reviews South African coal pillar design procedures in the light of 90 pillar collapses that have occurred since 1904. It shows that, while the current pillar strength formula is still valid within the original empirical range of Salamon[1], cognisance must be taken of local conditions.

Current South African coal pillar research is attempting to account for the variations in local conditions with the emphasis on the effect of discontinuities and pillar deterioration. It is suggested that a more holistic approach to pillar design be adopted to include a design methodology that examines the stability of the roof, pillar and floor of the underground workings.

Using this approach, deviations from the empirical database used by Salamon and Munro will be incorporated into the design methodology resulting in more stable underground workings.

Introduction

Coal pillar design is of primary importance for the safe, economic extraction of a valuable national resource. Early designs of pillar dimensions and road widths were based on experience obtained through trial and error. Some of the errors committed have had disastrous consequences in terms of loss of life, equipment and coal reserves.

In South Africa an intensive investigation into the strength of coal pillars followed the Coalbrook Colliery disaster of 1960. Salamon[1] and Salamon and Munro[2] detailed the statistical analysis of 27 collapsed and 98 intact pillar cases. A probabilistic notion of safety factor was used where:

$$\text{Safety Factor} = \frac{\text{Strength}}{\text{Load}} \qquad [1]$$

The values for strength and load must be regarded as predictions which are subject to error.

Salamon[1] thought it reasonable to suppose that the majority of mining engineers arrived at an acceptable compromise between safety and economic mining, with the optimum safety factor lying in the range where 50 per cent of the stable cases are most densely concentrated. This occurs between safety factors of 1,3 to 1,9 with the mean being 1,6. This value was recommended for the design of production pillars in South African bord-and-pillar workings.

Load is calculated using the modified cover load or Tributary Area Theory where each individual pillar is assumed to carry the weight of the overburden immediately above it. This assumption applies where the pillars are of uniform size and the panel width is larger than the depth to the seam. These conditions are fulfilled by the majority of bord-and-pillar panels in South African collieries.

Strength is taken to mean the strength of a coal pillar as opposed to the strength of a coal specimen. The formula for strength was given as:

$$\text{Strength} = k\, w^{\alpha}\, h^{\beta} \qquad [2]$$

where k = 7 176 kPa, α = 0,46 and β = -0,66.

The scatter of results was said by Salamon to be due to three major causes:

- natural causes—that is variations in coal strength, seam structure and the quality of the roof and floor,
- the approximate nature of the strength calculation,
- human error.

Salamon[1] emphasized that the pillar strength formula was essentially empirical and therefore should not be applied beyond the range of data used to derive it. Furthermore, the assumption in the formula of one average strength for all coal seams was recognised by him as a possible limitation.

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Salamon[3] in 1982 extended his pillar strength formula equation [2] to take cognisance of the increasing ability of a pillar to carry higher loads with an increasing width-to-height ratio.

The strength of a pillar given by Salamon's extended formula is:

$$\sigma_S = k\frac{R_0^b}{V^a}\left\{\frac{b}{\varepsilon}\left[\left(\frac{R}{R_0}\right)^{\varepsilon} \pm 1\right] + 1\right\} \qquad [3]$$

where R_0 is the critical width-to-height ratio
$\in$ is the rate of strength increase
a is 0,0667
b is 0,5933
V is pillar volume

Laboratory tests on sandstone specimens were analysed by Wagner and Madden[4] to examine the suitability of the new formula, known as the squat-pillar formula, to predict the strength increase with increasing width-to-height ratios. The squat-pillar formula was found to fit the laboratory results well; although these laboratory results cannot be related directly to coal pillars because of the difference in the material, scale, and time taken to test the samples, the general trend can be assumed to be similar.

Salamon and Wagner[5] suggested that the squat-pillar formula could be used with the critical width-to-height ratio (R_0) taken as 5,0 and $\in$ could be taken as 2,5, although a realistic estimate was more difficult to determine for the latter. The use of a value of 5 for R_0 was based on the fact that no pillar with a width-to-height ratio of more than 3,75 was known to have collapsed in South Africa up to that time.

Madden[6] re-evaluated the coal pillar design procedure in the light of back analysis of 17 additional collapsed pillar cases since 1967 where the coal pillar was considered to be the cause of the collapse.

Two significant features emerged from this analysis of the collapsed pillar cases. Firstly, pillars at depths shallower than 40,0 m, with widths of less than 4,0 m and a percentage extraction in excess of 75 per cent are prone to pillar collapse even when the designed safety factor is higher than 1,6. These three parameters are interrelated, and caution should be used when designing pillars at shallow depth. The effects of blast damage, geological discontinuities, weathering, or weak layers within the pillar influence the strength of small pillars more dramatically than they do larger pillars. Salamon and Oravecz[7], recognising the dramatic effect of a small reduction in pillar width when the pillar is less than 4,5 m in width, suggested that no pillar should be mined with a width of less than 3,0 m and that pillars between 3,0 m and 4,5 m in width should have a safety factor of at least 1,7.

Madden (6) suggested that at depths of less than 40,0 m, pillar widths should preferably be greater than 5,0 m, the width-to-height ratio should be in excess of 2,0 and the percentage extraction be less than 75 per cent. In addition, a safety factor of more than 1,6 should be maintained.

Current South African coal pillar research

The current pillar design project has attempted to develop a design procedure to take cognisance of different geological and structural factors, as well as the influence of the surrounding strata. The initial procedure was a visual rating system with the aim of this method being to rank pillar performance of an area over time by accounting for the pillar's ability to remain intact at a given load level. This method has the advantage that the local conditions of strata and structure can be included, while disadvantages are that the classification system is subjective, limited to a narrow range of stress levels and can only be applied to low pillar width-to-height ratios.

Emphasis has been placed on determining the strength of individual coal seams by means of 950 laboratory based strength tests. The test samples were taken from 12 blocks of coal obtained from four different seams. The original purpose was to identify whether laboratory-based testing could identify differences in seam strength. While relative differences in material strength may be obtained, particularly in the 300 mm sized specimens, laboratory-based testing results are limited in their application to full sized pillars. Statistical analysis of the laboratory test results showed a statistically significant variation in strength. However, the variation in strength occurs within a tight range and it was considered that one common strength is not unrealistic based on the results obtained from the 12 blocks.

A complete review of the back analysis of collapsed pillar cases was initiated. The first coal pillar collapse was recorded in South Africa in 1904. Salamon found 50 cases by 1967, however, only 27 of these were used due to either unreliable information or because of weak roof conditions at shallow depth. Salamon's cases were where the coal pillar was the weakest element with strong surrounding roof and floor. Madden[6] found that 38 pillar collapse cases had occurred since 1967 and excluded 21 cases where weak roof or coal deterioration was thought to have been contributory to the collapse. Again the coal pillar was the weakest element and all cases had competent roof and floor. From 1988 to 1996 an additional 23 pillar collapses have occurred. In an attempt to develop an understanding of the effect of the floor and roof strata, and other influencing factors, it was decided to plot all collapses where reliable information existed concerning the pillar design geometries.

Figure 1 shows the frequency of the collapsed pillar cases versus their designed safety factor. The categories indicated in Figure 1 are as broad as possible. Several observations can be made from this Figure. Firstly, pillar collapses have occurred with very high, up to 5,6, designed safety factors. In fact, 35 of the 90 pillar collapses have occurred with safety factors in excess of a designed value of 1,6. Secondly, the majority of the collapsed pillar cases occur in Salamon's original empirical range and have a designed safety factor of less than 1,6. In eight cases the pillars stood for between 30 and 50 years at designed safety factors of between 0,91 and 1,37 before failing.

It should be noted that the majority of coal produced underground in South Africa comes from the Witbank and Highveld Coalfields. In these coalfields Salamon's strength formula is performing well in the design of stable pillar systems. However, coal is produced underground in a variety of other coalfields with varying conditions. Examination of the collapsed cases with designed safety factors higher than 1,6 suggests that they can be broadly grouped into geographic areas.

In total, 90 cases were considered out of 111 pillar collapse cases recorded in South Africa. For example, some 29 collapsed pillar cases have occurred in the Vaal Basin

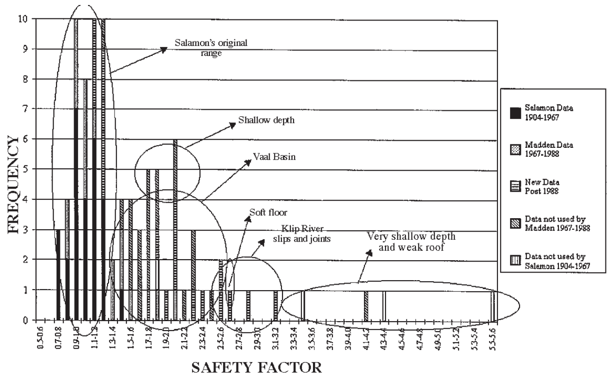

Figure 1—Frequency of pillar collapse versus design safety factor

Coalfield since 1967. Some of these cases had high safety factors but failed due to some form of deterioration over time (van der Merwe[8]). Madden[6] excluded 19 cases from the Vaal Basin Coalfield in the re-evaluation of pillar design conducted in 1988. The mechanism resulting in pillar deterioration is not understood and requires further research.

Major discontinuities occurring in the coal seam were considered the reason for the five pillar collapses that occurred in the Klip River Basin, Figure 1. In these cases the discontinuities were smooth, slickensided, continuous over tens of metres and occurred in two to three different orientations within a pillar. These cases failed soon after mining despite high safety factors and high pillar width-to-mining height ratios. Other reasons for pillar collapse have been attributed to soft floors or where depths shallower than 40 m resulted in very small pillar widths.

Figure 2 shows the 90 collapsed cases in terms of frequency versus the pillar width to mining height ratio. Of note is that 25 cases occurred with width-to-height ratios in excess of 3,5.

The majority of these occurred in the Vaal and Klip River Basins. An important observation is that no collapses have occurred in the squat pillar range where the pillar width to mining height ratio exceeds five. The squat pillar formula has been in use for over 10 years in at least 15 collieries throughout South Africa.

The number of pillars involved in each collapse is shown in Figure 3. Whilst the majority of cases involve between 50 and 200 pillars, several large collapses have occurred. At Coalbrook Colliery some 7 700 pillars collapsed, 4 400 within 5 to 15 minutes.

Figure 4 shows the frequency versus the time taken between mining and pillar collapse. About 50 per cent of the collapse cases occur in the first four years. However, pillar collapse has occurred some 50 years after mining.

Figure 5 shows the designed safety factor versus the time interval between mining and collapse. No correlation is apparent from this figure. However, the importance of time cannot be underestimated.

Coal pillars standing for long periods of time have been observed to deteriorate. The rate of deterioration is not known, however the potential impact in terms of the effect on the surface, the environment, and safety of the work force exists. As some pillars are designed with the intention of future extraction, the loss of strength over time could jeopardise the safety of the pillar extraction crew. Also, collapse of old panels can cut access ways to production panels, as occurred in Swaziland where a pillar collapse trapped some 30 men who eventually escaped via a borehole drilled from the surface next to a refuge bay.

The strength of a coal pillar is a function of numerous parameters including: seam strength, geometry, discontinuities, the contact conditions between the pillar and the roof and floor, weathering of the coal seam, time, loading rate, geology, the material characteristics of the roof and floor strata as well as the mining method employed.

Salamon's back analysis of collapsed pillar cases between competent roof and floor strata inherently contained all of these parameters and remains valid within its empirical range or where similar conditions are found. Should some of these parameters be dominant and outside of the empirical range, pillar stability may not result.

Thus, cognisance of the local conditions must be taken into account. Current South African research is attempting to

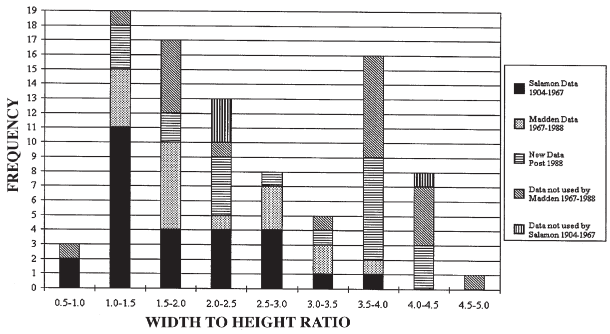

Figure 2—Frequency of pillar collapse versus width to-height ratio

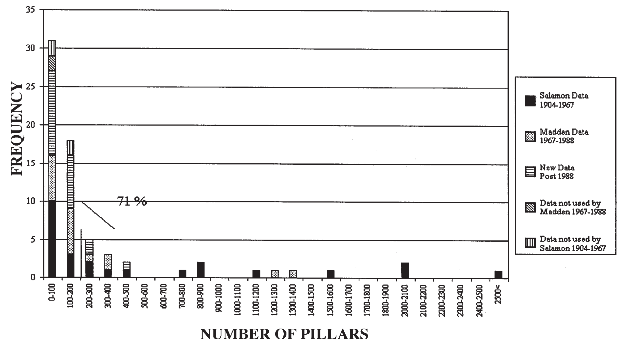

Figure 3—Frequency versus number of collapsed pillars

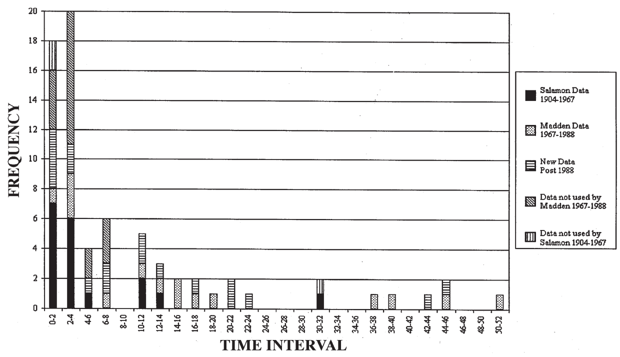

Figure 4—Time interval versus frequency

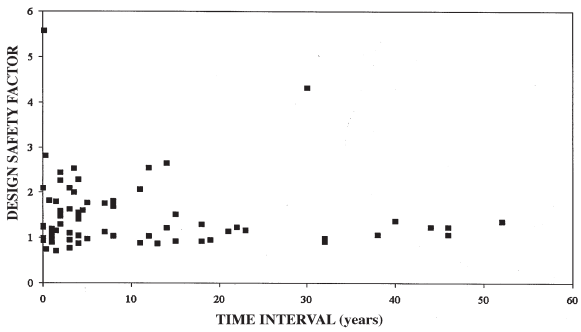

Figure 5—Design safety factor versus time interval

understand the effect of local conditions in terms of discontinuities and the extent of pillar deterioration. It would be beneficial for the research to be extended to include a holistic approach to pillar design where each element of the pillar system, consisting of the roof, pillar and floor, is examined in terms of stability. There would be a need to assess each parameter in terms of Salamon's original cases and to compare these with the collapsed cases since 1967 to define deviations which may be incorporated into a pillar system design procedure.

Future research directions

It has been seen that many of the collapses of bord-and-pillar workings can be clearly attributed to causes that indicate that the pillar was not the weakest element. For example, in the collapsed cases from the Klip River Coalfield, where the pillars appear to be the weakest element, it is likely that the mechanism of failure was dominated by the orientation and properties of the discontinuities rather than the nominal seam strength.

The current empirical approach is limited to the cases where the pillar is the weakest element. Even when this is clearly not the case, the design engineer currently has limited design criteria with which to address the problem. With the new information discussed in this paper, it is now possible to consider the idea of expanding the pillar formula into a pillar system design procedure. This holistic approach would, in essence, explicitly consider the stability of the floor, the pillar and the roof, within the overall loading environment, including all relevant parameters for each component.

There is, of course, some interaction between these elements. These interactions are complex, and not amenable to analytic solution, especially in jointed country rock and pillars. These problems can be analysed with the aid of computer software.

There is scope for the creation of generic guidelines for a pillar system design procedure. This concept is illustrated in Figure 6. A proposed full design procedure is illustrated from the pre-mining phase to the detailed phases concurrent with production. In the flow chart, the 'Pillar Design' box currently incorporates adaptations for mining method, shallow working guidelines and the provision for the squat pillar formula depending on pillar geometry. However, for a design procedure that can reliably provide stable pillar systems across a wide spectrum of conditions, consideration of all the inter-related components illustrated in Figure 6 is essential.

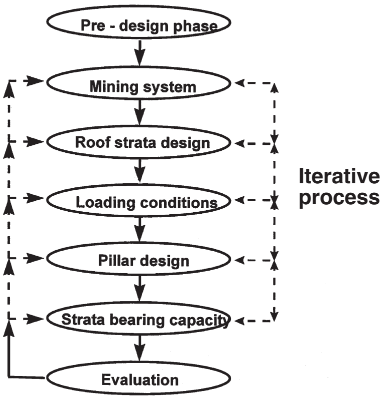

Figure 6—Conceptual pillar system design methodology

Conclusion

Salamon's strength formula has been successfully applied in coal pillar design for some 30 years. However, recent pillar collapses have occurred outside of Salamon's original empirical range. Back analysis of 90 collapsed pillar cases in South Africa has shown that collapses with high designed safety factors have occurred at shallow depths, due to weak roof and floors or in similar geographic regions where one or more of the features appear to be dominant.

Coal pillar strength is a function of many parameters including—geology, discontinuities, seam strength, time, weathering, loading rate and the surrounding strata properties. However, pillar system stability is also affected by the surrounding strata. Where one of these parameters becomes dominant, the stability of the pillar system may not be predicted by the current pillar design methodology.

Cognisance of local conditions deviating from the current empirical range must be incorporated into a pillar design methodology. Coal pillar research in South Africa is presently concerned with investigating the influence of local conditions on pillar strength.

Future research should incorporate all aspects influencing stability including a holistic approach to how the roof, pillar and floor components may affect stability. In this manner long term stability of underground workings will result in a safer working environment.

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