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Revised strength factor for coal in the Vaal basin

by J.N. van der Merwe*

SYNOPSIS

The South African coal-mining industry uses a uniform safety-factor formula for non-squat pillars, incorporating a coal-strength constant that was derived empirically by Salamon and Munro in the 1960s. The constant is 7,2 MPa. Since that time, collapses of pillars at relatively high safety factors have occurred in the Vaal Basin. Analysis of the post-1960s' collapses indicated that the strength constant for the Vaal Basin is 4,5 MPa. A crude method for the prediction of the minimum life span of pillars in the Vaal Basin is presented.

SAMEVATTING

Die Suid-Afrikaanse steenkool mynbou-industrie gebruik 'n eenvormige veiligheidsfaktor-formule vir nie-plat pilare, wat 'n konstante vir steenkoolsterkte insluit wat empiries bepaal is deur Salamon en Munro in die 1960s. Die konstante is 7,2 MPa. Sedertdien het swigtings van pilare met relatief hoë veiligheidsfaktore in die Vaalkom voorgekom. Analise van die na-1960 swigtings het aangetoon dat die konstante vir die Vaalkom 4,5 MPa is. 'n Growwe metode vir die voorspelling van die minimum leeftye van pilare in die Vaalkom word aangebied.

INTRODUCTION

The Vaal basin has long been recognized as a difficult area for coal mining in South Africa. Mines like Coalbrook, Sigma, and Cornelia are characterized by roof falls and pillar scaling. The disastrous pillar collapse of 1960 at Coalbrook prompted a full-scale investigation into coal-pillar stability in South Africa in general, which resulted in Salamon and Munro's well-known and widely accepted safety-factor formula[1].

The success of the formula has been commented upon by researchers like Madden[2], who expanded it to cater for pillar width-to-height ratios greater than 5. Madden concerned himself mainly with the increase in strength of wide pillars.

South Africa's coal-mining industry is unique in that the same formula with the same constants is applied in all the coal seams in all the coalfields. Although the use of the formula is not required by law, it is required by the various inspectorates countrywide and is therefore binding in practice.

It has long been believed that the different coal seams vary in strength. Research into this topic has often been called for, mainly by mines mining stronger coal, who can therefore adapt the general formula and thereby increase their extraction without sacrificing safety.

A number of pillar collapses have been recorded in the Vaal basin coalfield by Coalbrook, Sigma, and Cornelia Collieries. During 1991, Sigma Colliery experienced three separate, unrelated collapses within a period of four months. One was in an area where both double-seam mining and floor coaling had been done. In the other two cases, only one seam was mined and the safety factors ranged from 1,7 to 2,8.

These collapses prompted an investigation, during the course of which it became apparent that there were similarities between the collapses. When the data from those mines were combined, certain characteristics of pillar failure in the region could be determined.

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Because the commonly used safety factor in its present form was obviously not suitable for the region, a new strength constant for the formula (the k-factor) was found. This also led to the development of the Pillar Life Index, a crude empirically-derived method for indicating the relative minimum life of pillars.

The new constant was made only for the Vaal basin. No attempt was made to derive similar new constants for the other regions.

In general, long-term coal-pillar stability can be regarded as a problem internationally. The USA and the UK, for example, experience problems with the stability of very old pillars. This highlights an important advantage of high-extraction mining, which is that the surface can be allowed to subside in a predictable manner, facilitating planning and control.

REVIEW OF STANDARD FORMULA

This paper does not intend to repeat the work of Salamon and Munro[1] or that of Madden[2]. However, a few basic concepts have to be clarified. Only the Salamon and Munro formula will be discussed, as the pillar width-to-height ratios were less than 5.

Components of the Formula

Safety factor

Any safety-factor formula consists of two basic parts: one quantifying the strength of the structure, and the other the load imposed on it. The safety factor is then merely the ratio of strength to load:

$$SF = \frac{\text{Strength}}{\text{Load}} \quad [1]$$

Pillar strength

The general strength of pillars is represented by the expression

$$S = kw^{\alpha} h^{\beta} . \quad [2]$$

It was found by Salamon and Munro[1] after a comprehensive study that the values k = 7,2 MPa, α = 0,46, and $\beta = -0,66$ best described pillar strength in South African collieries. The expression that is used today is thus the following:

$$S = 7,2 \frac{w^{0,46}}{h^{0,66}}, \qquad [3]$$

where S = pillar strength in MPa,
w = pillar width in m, and
h = pillar height in m.

The k-factor is the one that describes the strength of the coal material.

It has been shown by several authors, including Bieniawski[3], that the strength of coal decreases as the size of the test specimen increases; however, it appears to level out as the size of the specimen approaches a cube measuring 1 m^3. The value of $k = 7,2$ MPa thus represents the strength of a cubic metre of coal, according to Salamon and Munro[1].

Pillar load

In the determination of pillar load, use is made of the tributary-area theory, which means that each pillar is considered to be responsible for bearing the weight of the overburden above it. Therefore,

$$L = \frac{0,025 H \, (w + B)^2}{w^2}, \qquad [4]$$

where L = load in MPa,
B = bord width in m,
w = pillar width in m, and
H = depth to floor height in m.

The constant 0,025 represents the unit weight of the overburden, and the rest of the expression is the volume of coal vertically above a pillar divided by the area of the pillar.

Determination of Norms

It is generally accepted that the safety factor should not be less than 1,6 for bord-and-pillar workings, and not less than 2,0 for main development. For the purposes of structures undermined on surface, higher values, usually 2,0 to 3,0, are required by the Department of Mineral and Energy Affairs. The requirement is loosely based on the sensitivity of the structure and the risk to people.

The norms were confirmed by plotting the cumulative normalized frequency curve for the safety factors of failed pillars, as shown in Figure 1, which represents the probability of having a stable layout[4].

Figure 1 is based on the safety factors of failed pillars (Vaal basin excluded). It coincides closely with the curve found by Salamon and Munro[1] for pillar failures prior to 1966. As can be seen, at a safety factor of 1, approximately 50 per cent of all pillars had failed, which confirms the validity of the formula. Furthermore, above a safety factor of 1,6, no further failures are shown, which indicates that 1,6 is a good safety factor for normal pillar workings.

It can thus be concluded that, in South Africa excluding the Vaal basin, the standard safety-factor formula is a good reflection of underground stability.

ANALYSIS OF PILLAR FAILURES IN THE VAAL BASIN

A disturbing number of pillar failures was recorded in the Vaal basin before and after 1966. Figure 2 shows the pillar failures in the Vaal basin against pillar age at failure, together with failures for the rest of the country.

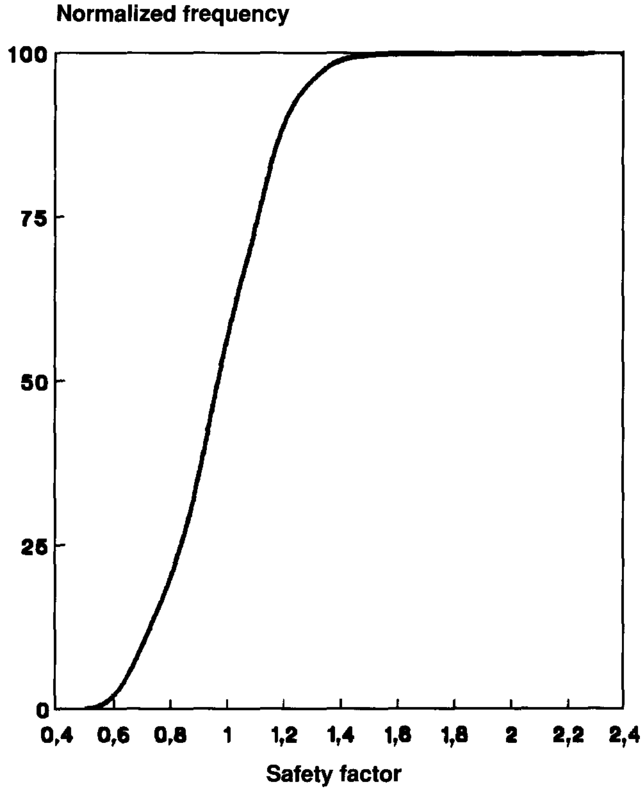

Figure 1—Normalized cumulative frequency curve for safety factors of failed pillars[4]

The failures in the Vaal basin are identifiable as a separate group, being characterized by higher safety factors and shorter lifespans than the other failures.

The rest of this paper deals with the failures in the Vaal basin as a separate group.

Pillar Stability and Safety Factor in the Vaal Basin

When the normalized cumulative frequency curve for the safety factors of the failed pillars is constructed, a disturbing feature comes to light, shown as the solid line in Figure 3. For comparative purposes, the broken line in this figure shows the curve for the rest of the country.

Although the curves are similar in shape, the curve for the rest of the country is spread about a safety factor of 1, while the values for the Vaal basin are spread about 1,6. Thus, at a safety factor of 1,6, there is a 50 per cent probability of failure for pillars in the Vaal basin, or the average safety factor for the failed pillars is 1,6. Where the curve for the rest of the country indicates no failure above a safety factor of approximately 1,6, that value for the Vaal basin is 2,3.

As pillars cannot fail when the strength exceeds the load, it must be concluded that the method of calculating the safety factor is incorrect, and therefore that the standard safety-factor formula is not applicable to the Vaal basin.

Alternative *k*-constant for the Vaal Basin

Because there is no reason to believe that the calculation method for pillar stresses in the Vaal basin should differ from that for the rest of the country, the problem must lie in the calculation of pillar strength.

In view of the remarks made earlier about pillar strength, the k-constant is the most likely to be incorrect. Salamon[5] remarked that k is likely to be different for different coal

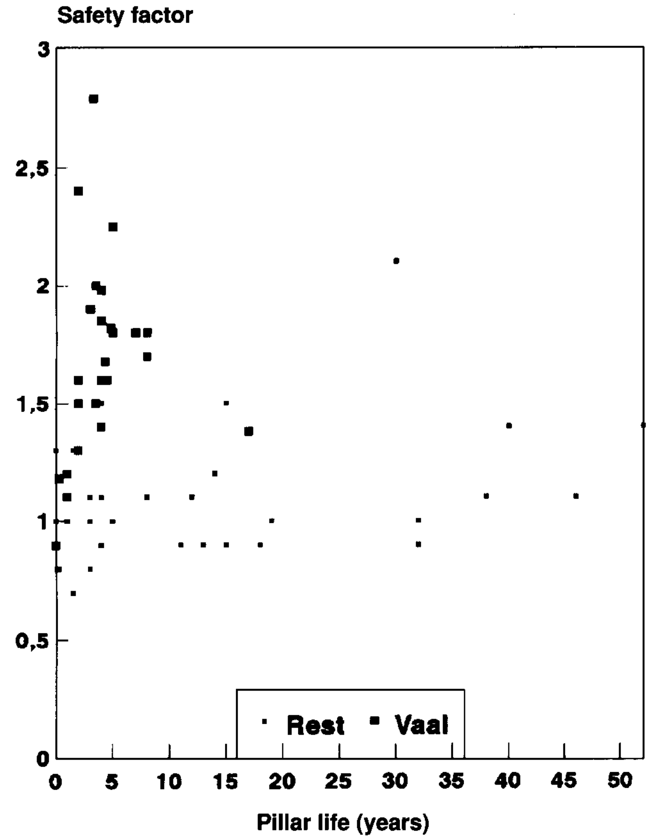

Figure 2—Safety factor versus pillar life span at failure

seams. He stated that the uniform constant had to be used, as there was insufficient data at the time to derive different constants for different regions or seams.

The safety factors in the Vaal basin were then recalculated with k = 4,5 instead of 7,2 MPa, and the normalized cumulative frequency curve was redrawn. This is shown as the solid line in Figure 4.

Now the curve for the Vaal basin corresponds fairly well to the curve for the rest. The conclusion is therefore that, for the Vaal basin, k = 4,5 should be used.

For the record, the strength of pillars in the Vaal basin should then be calculated by use of the expression

$$S = 4,5\frac{w^{0,46}}{h^{0,66}}. \quad [5]$$

Figure 5 reinforces the validity of the new constant; pillar strengths calculated according to the standard formula are compared with those obtained by use of the new constant. Pillar strengths are plotted against pillar loads. As can be seen, the strengths obtained by use of the standard formula all fall well above the line indicating a safety factor of 1. Strengths obtained with the new constant are more evenly distributed around the same line.

MECHANISM OF FAILURE

General Nature of Failure

As can be seen from Figure 2, pillars fail after a period; they seldom fail immediately. Observations both underground and in laboratories show that failure is preceded by progressive deterioration.

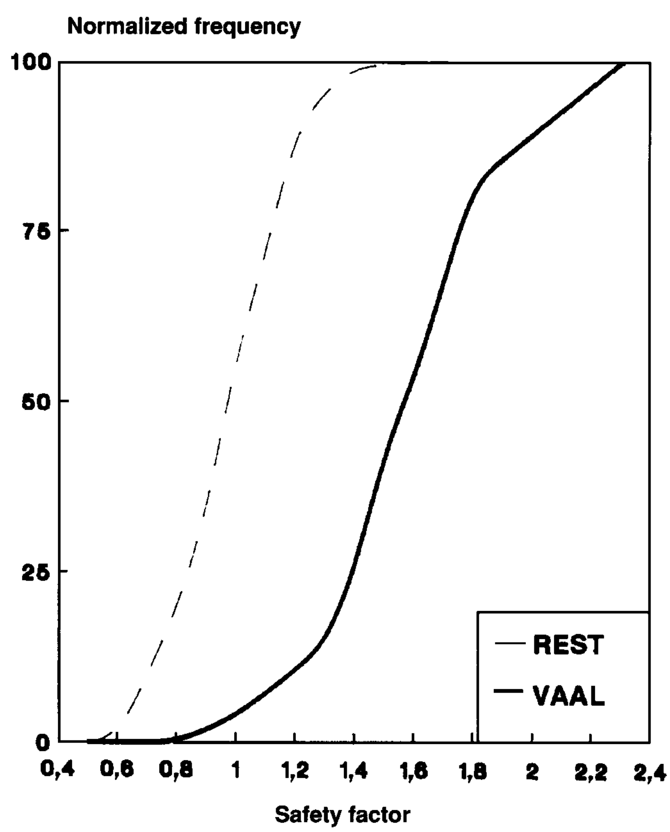

Figure 3—Comparison of safety factors of failed pillars in the Vaal basin and elsewhere

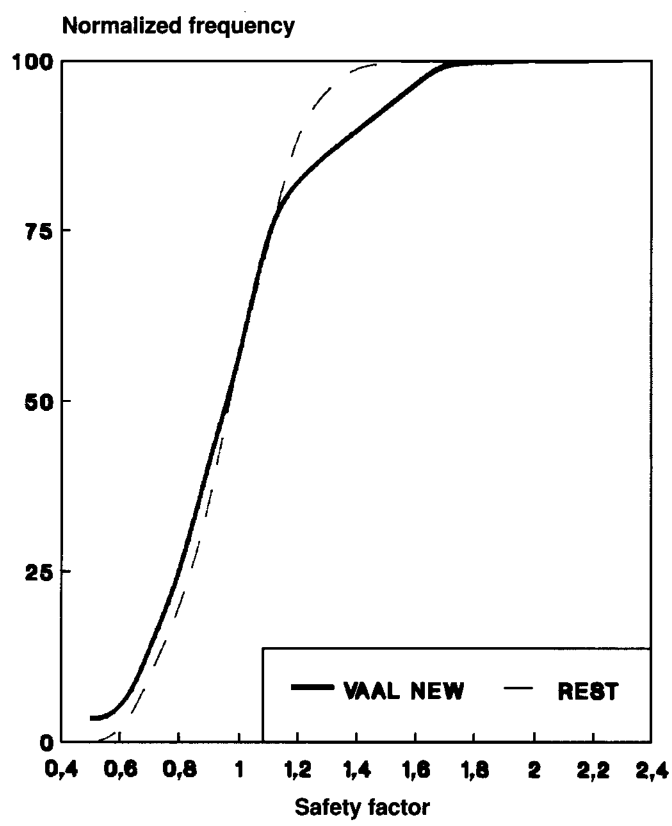

Figure 4—Comparison of safety factors for the rest of the country with safety factors in the Vaal basin as calculated with the new *k*-factor

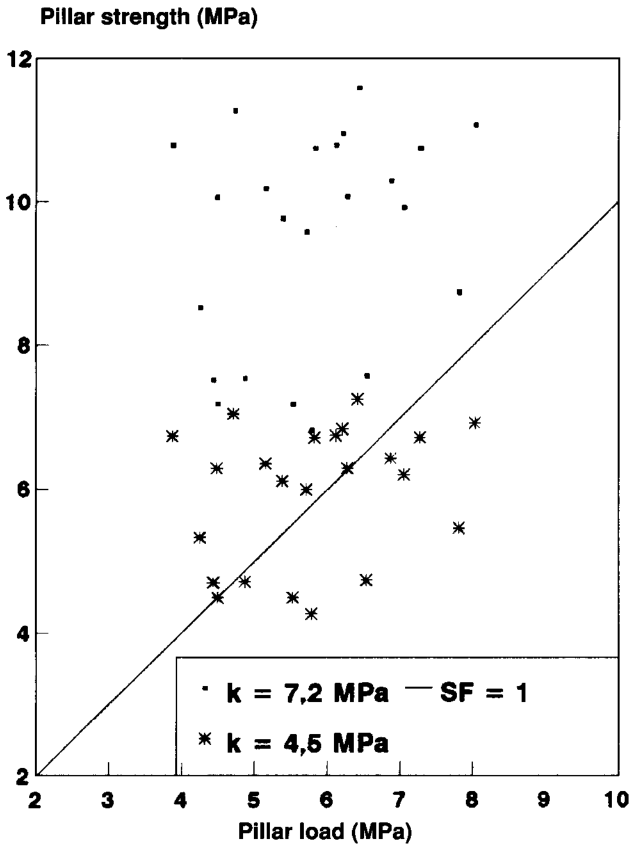

Figure 5—Pillar strengths calculated with two values for *k* against pillar loads

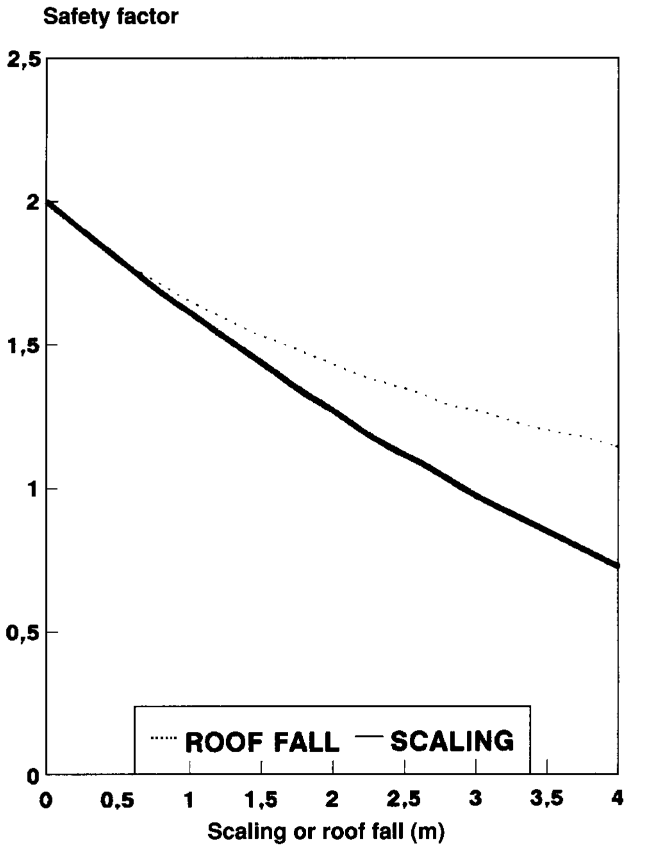

Figure 6—Comparison of the effects of roof falls and pillar scaling on safety factors for *H* = 100 m, *h* = 3 m, and *B* = 5,6 m

A pillar cannot fail if the real safety factor is greater than 1. Only if the safety factor is reduced to a value of less than 1 will failure occur. It is important for the mining engineer to understand the failure process for two reasons: to decide on preventative measures against failure where pillars have already been created, and to attempt to predict the time at which failure will occur.

Pillar Scaling and Roof Falls

Underground workings in the Vaal basin are characterized by pillar scaling and roof falls. Both phenomena change the geometry of the pillars and therefore the safety factors.

The respective contributions of the two phenomena to the reduction of safety factors are shown in Figure 6, which also shows how the safety factor of a pillar with an initial safety factor of 2 at a depth of 100 m, height of 3 m, and bord width of 5,6 m is reduced with progressive pillar scaling or progressive roof falls. Each variable was changed while the other was held constant.

This is an example, and the exact figures are valid only for the quoted conditions. It nonetheless indicates that a certain amount of pillar scaling will have a greater detrimental effect on pillar stability than the same height of roof fall.

It has also been observed underground that scaling is much more common than roof falls. In most areas of the Vaal basin, virtually all the pillars scale, while roof falls tend to be restricted in extent and in occurrence. It appears that more roof falls occur in the Vaal basin than elsewhere but, even in that area, only some pillars are affected by roof falls, while virtually all pillars are affected by scaling. The author has witnessed a number of instances where special measures have had to be taken to halt the progress of pillar failure in areas where roof falls had not occurred.

Scaling Required to Reduce Safety Factor

The amount of scaling needed to reduce a pillar's safety factor to a value of less than 1 is a function of several variables, such as depth, mining height, initial pillar width, and bord width.

For instance, the amount of scaling required for pillars with a certain fixed safety factor is not constant, but is a function of depth. This is illustrated in Figure 7, where the decrease in safety factors for two pillars, with the same initial safety factor (2) but situated at different depths, is shown for progressive scaling.

TIME OF FAILURE

Amount of Scaling

As it is accepted that no pillar with a real safety factor in excess of 1 can fail, it was assumed that failure occurs only when sufficient scaling has taken place to reduce the safety factor to a small value. The 'small value' to ensure failure was deduced to be 0,3 (Figure 4). At a value of 0,3, all pillars had failed. The data therefore suggest that, at a safety factor of 0,3, all pillars will definitely fail. The amount of scaling required, *d*, to reduce the safety factor to 0,3 can be determined from the following:

$$L = \frac{0,025\,H\,(w+B)^2}{(w-d)^2} \qquad [6]$$

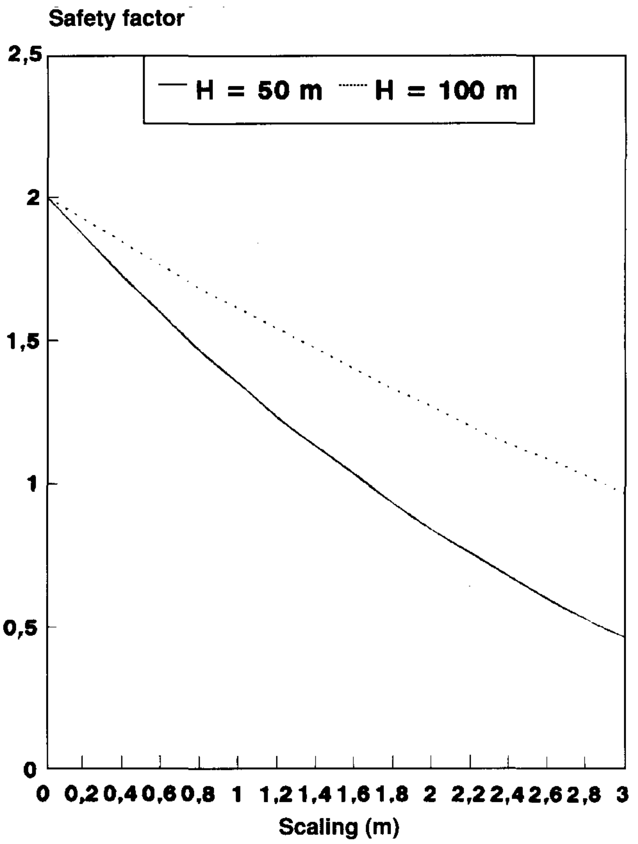

Figure 7—Effect of pillar scaling on safety factors for *h* = 3 m and *B* = 5,6 m for different depths of mining

$$S = 4,5 \frac{(w-d)^{0,46}}{h^{0,66}} \quad [7]$$

$$SF = \frac{S}{L} = 0,3. \quad [8]$$

Therefore,

$$d = w - [0,0742\, h^{0,268} H^{0,407} (w+B)^{0,813}]\,. \quad [9]$$

Note that the equation is somewhat more complex for pillars that are not square; it is shown here in the simplified form for square pillars.

The amount of scaling, *d*, is that value which satisfies equation [9]. It is best found by iteration for pillars that are not square. The symbols are shown in Figure 8.

The expected minimum lifespan of pillars can now be estimated if the rate of scaling is determined.

Rate of Scaling

The scaling rate is possibly a function of several variables, some of which can easily be quantified and some not so easily. Among the more difficult ones are climatic conditions, absence or presence of sidewall support, chemical composition of coal, etc. The easily quantifiable ones are pillar stress, mining depth, mining height, etc.

Correlations were sought between the rate of scaling (defined as the quotient of amount of scaling required and age of pillars upon failure) and several combinations of the measurable parameters for the known failed pillars. Not all the data could be used for this part of the investigation, since the pillar lives at the time of failure were uncertain in some cases. Furthermore, the simplifying assumption was made that the rate of scaling is constant.

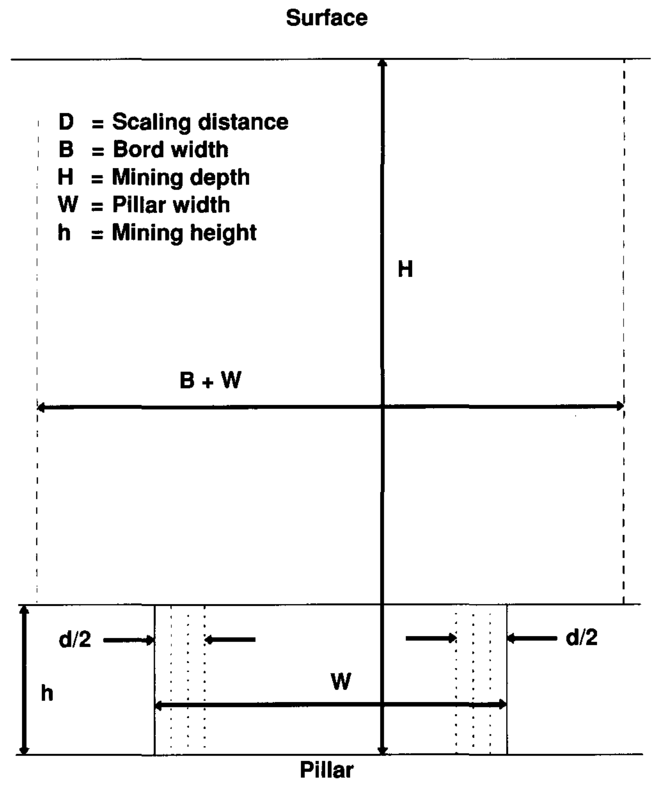

Figure 8—Explanation of geometrical symbols used in the text

Virtually no correlation was found with safety factor, pillar stress, pillar strength, depth, pillar width, bord width, or any combination of them. There was, however, a surprisingly good correlation with mining height.

Figure 9 shows the relationship between the rate of scaling and mining height for failed pillars in the Vaal basin. The correlation coefficient between the curve and the actual cases was 0,9.

The expression for the rate of scaling (metres per year) is

$$R = 0,015h^{3,7}\,, \quad [10]$$

where R = rate of scaling in metres per year and
h = mining height in metres.

As the curve was found empirically from the data on failed cases, it implies that the rate of scaling is the *maximum* rate, and will thus reflect the *minimum lifespan* of pillars.

That rate will be influenced by climatic conditions and the chemical composition of the coal material, which, in turn, govern the rate and extent of chemical weathering. The rate will also be retarded by maintenance in the form of sidewall support, or accelerated by the loading away of scaling debris from pillar sidewalls.

Roof falls in the area generally take the form of sudden collapses of more than a metre. While scaling will take place at a certain steady rate, the safety factor will suddenly decrease when a roof fall occurs, perhaps triggering progressive pillar collapse. Collapse may also be triggered by a sudden change in climatic conditions, such as during changes of season.

Therefore, pillar life cannot be quantified accurately. The minimum pillar life should rather be regarded as an *index*,

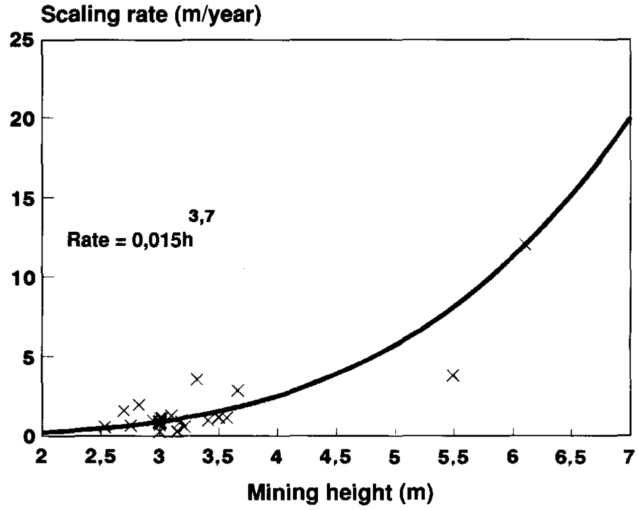

Figure 9—Scaling rate as a function of mining height

indicating the priority in which action, if any, is required, should be taken.

Prediction of Pillar-life Index

Vast areas have been mined according to a design based on a sub-optimal strength constant, and measures to prevent pillar failure, or minimize its consequences, will have to be taken in certain places.

It should be realized that the method for predicting pillar life cannot yield absolute answers for pillar lifespans. Calculating the pillar-life index of pillars will nonetheless aid management in deciding priorities.

The method to be followed can basically be broken down into three steps:

- determination of d from equation [9]
- determination of R from equation [10]
- calculation of pillar-life index = d/R.

These calculations can be laborious (especially the iterations called for if pillars are not square). A computer program has therefore been written for this purpose.

DISCUSSION

The pillar collapses at Sigma Colliery occurred because the k-constant in the generally applied safety-factor formula, which was used to design the pillars, is not valid for the region. Before the collapses proved otherwise, there was no reason to doubt the applicability of the formula to that mine. The collapses were thus not due to negligence, wilful unsafe mining practice or bad judgement by the mine management.

The generally applied k-constant was not regarded as being the ultimate answer at the time of the development of the formula by the team under the leadership of Professor Salamon, then of the Chamber of Mines Research Organization. In the absence of sufficient information at the time, it was not possible to derive different factors for different regions or coal seams.

The information now available has shown that the k-constant for the Vaal basin should equal 4,5 MPa, and not 7,2 MPa as used in the general formula.

It has also been shown that k = 7,2 MPa is a reasonable value to use for the rest of the country. No attempt was made to derive k-values for specific seams or regions within that broad classification.

Some reactive measures may now be required as vast areas have been mined with pillars whose safety factors are lower than intended. In order to indicate where action is needed, a procedure has been developed to indicate the minimum lifespan of pillars. The pillar-life index should be regarded as a *relative* index, indicating the order in which action should taken.

Several bord-and-pillar panels were mined with the bord-and-pillar method for no reason other than that suitable high-extraction methods were not in use at the time of mining, and not necessarily to protect structures on surface. In the majority of cases, therefore, no stabilizing measures are required.

Where the mine's infrastructure or other surface structures are not involved, there is little reason not to allow pillars to collapse. Where collapses have to be avoided, and where investigation by the methods now available indicates that they may occur, the stabilizing measures to be implemented should be based on factors such as the accessibility of the area, and the need to keep the entries serviceable or open.

With the new k-factor for the safety-factor formula, it is now possible to design mine layouts that will eliminate the collapses being experienced. This will have a negative effect on the reserve utilization with bord-and-pillar mining, and is therefore a further reason for the use of high-extraction mining methods to the maximum practicable extent.

It can be concluded that, following the pioneering work of the early researchers, the science of strata control in coal mining has advanced sufficiently for a problem of this magnitude to be brought under control. This exercise is also proof of the responsible attitude of mine operators in South Africa, who voluntarily employ strata-control experts in-house, where they are able to react swiftly to problems that could pose safety hazards.

This experience emphasizes the need for the present effort to determine different strength values for different coal seams or regions. Perhaps the empirical methods will be difficult to apply in areas with strong coal, where no database of failed pillars exists. Other methods may thus have to be developed.

While the pillar-life index demonstrated is still a crude method of calculation, it nonetheless indicates a possible alternative to the concept of a safety factor, by permitting the prediction of the lifespan of a pillar layout. No reasonable safety factor can be relied upon to indicate the stability of a pillar for ever. Perhaps pillar stability should be viewed in the light of the passage of time, rather than as a ratio of load to strength at any particular moment.

An inherent problem in the use of the empirical approach to the determination of pillar strength characteristics is the differentiation between failed and stable pillars. That distinction can be made only at a particular time. Pillars classified as stable at the time of investigation may fail later. The characteristics of the database will thus change.

According to Salamon[6], a time limit for distinguishing stable pillars of 7 to 10 years was assumed during the 1960s' investigation. This was not unreasonable, as the intention at the time was to prevent another disaster like Coalbrook, and not to develop a formula for designing pillars that would be stable for ever.

The real challenge may be to design stability around the time factor.

REFERENCES

1. SALAMON, M.D.G., and MUNRO, A.H. A study of the strength of coal pillars. *J. S. Afr. Inst. Min. Metall.*, Sep. 1967. pp. 55–67.
2. MADDEN, B.R. Re-assessment of coal pillar design. *Proc. S. Afr, Inst. Min. Metall.* Summer School, Witbank, 1989.
3. BIENIAWSKI, Z.T. *In-situ* strength and deformation characteristics of coal. *Engng. Geol.*, vol 2. 1968. pp. 325–340.
4. MACCOURT, L., MADDEN, B.J., and SCHÜMANN, E.H.R. Case studies of surface subsidence over collapsed bord-and-pillar workings in South Africa. *Proc. Symp. The Effect of Underground Mining on Surface*, South African Nat. Group on Rock Mechanics, Johannesburg, Oct. 1986. pp. 25–33.
5. SALAMON, M.D.G. Present state of rock mechanics in bord and pillar coal mining. Chamber of Mines Research Organization, *Research Report* no. 2/69, Jan. 1969.
6. SALAMON, M.D.G. Personal communication, 1992.

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6 May 1993 – Technical Visit
Venue: Landau Replacement Projects: Pit and Plant
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14 July 1993 – Annual General Meeting and Dinner
Venue: Kriel Club
Time: 19:00 for 19:30

16 September 1993 – Technical Visit and presentation of 2 papers on Steel Metallurgy and Steel Marketing
Venue: Highveld Steel Plant
Speakers: To be announced
Time: 15:00; presentation of papers at 17:00

November 1993 – Gala Dinner
Venue: Secunda
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27 April 1993 – 1-day Technical Visit to Premier Diamond Mine
Venue: De Beers' Premier Diamond Mine, Cullinan
Time: 08:00
Cost: R65,00
Closing date: 21 April 1993

13 May 1993 – Presentation: Lesotho Highlands Water Project by A.G. Davies
Venue: Johannesburg Country Club
Time: 17:00 for 17:30

24 June 1993 – 1-day Technical Visit to Haggie Rand Limited—Jupiter Plant
Time: 09:30
Cost: R30,00 for Members, R40,00 for Guests
Closing date: 17 June 1993
Directions will be sent to successful applicants

20 July 1993 – Annual General Meeting
Guest Speaker: Mr Gary Maude (Genmin)
Details to be announced

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12 May 1993 – Annual Visit
Details to be announced

14 July 1993 – Annual General Meeting
Details to be announced

15 September 1993 – Mini Visit
Details to be announced

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26 May 1993 – Extractive Metallurgy Research at Anglo American Research Laboratories
Guest Speaker: Paul Dempsey (Anglo American Research Laboratories)
Venue: University of Pretoria

26 July 1993 – Annual General Meeting
Venue: University of Pretoria
Guest Speaker: President of The South African Institute of Mining and Metallurgy
followed by:
Seminar on Heat Treatment of Steel
Venue: University of Pretoria
Guest Speakers: Prof. G.T. van Rooyen
Prof. G. Pienaar

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25–27 August 1993 – Minerals Engineering '93
This event is being organized by the Western Cape Branch in collaboration with Dr Barry Wills of the Camborne School of Mines
Venue: Cape Sun
Details to be announced

26 August 1993 – Annual General Meeting and Banquet
Details to be announced

6–8 October 1993 – Materials into the 21st Century
Venue: Van Riebeeck Hotel, Gordon's Bay
Details to be announced

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