WRITTEN Contribution

Revised strength factor for coal in the Vaal basin

by J.N. van der Merwe*

CONTRIBUTION BY H. WAGNER† AND T.T. OZAN‡

The paper by Dr J.N. van der Merwe makes an important contribution to the design of bord-and-pillar workings in the Vaal basin. It has been recognised for some time that the strength of coal seams in the Vaal basin is markedly lower than that of coal seams in other coal-mining districts in South Africa. However, there was insufficient data to quantify how much weaker the extensively jointed coal in the Vaal basin is. A number of recent pillar collapses that occurred at Sigma colliery, the only remaining underground colliery in the Vaal basin, provided Dr Van der Merwe with an opportunity to make this assessment.

The well known coal-pillar strength formula by Salamon and Munro[1] was derived on the basis of a statistical analysis of 27 collapsed and 98 stable bord-and-pillar geometries from collieries of the Transvaal Coalfields and the Vaal basin (OFS collieries). Salamon and Munro found that the strength of coal pillars could be described by the following expression:

$$S = k\,h^{\alpha} w^{\beta} \qquad [1]$$

Employing the method of maximum likelihood and expressing the pillar dimensions in metres, the following values for the parameters k, α, and β were obtained by Salamon and Munro:

$$k = 7176 \text{ kPa}, \ \alpha = -0{,}66, \ \beta = 0{,}46.$$

In terms of equation [1] the strength of a coal pillar is determined not only by the strength of the pillar material, k, but also by the parameters α and β, which describe the influence of the pillar geometry, h and w, and the important effects at the interface between the coal seam and the surrounding strata. The lower strength of coal pillars in the Vaal basin could, therefore, be caused by a lower k-value, or by changed values of parameters of α and β, which among others describe the confinement of the centre core of the pillar by the cohesion and friction that act at the interface between the pillar and the surrounding strata. Alternatively, a combination of these factors could be responsible.

Against this background, caution has to be exercised in attributing the lower strength of the coal pillars in the Vaal basin solely to the strength properties of the pillar material, as proposed by Dr Van der Merwe. The correct approach would be to subject the data from collieries in the Vaal basin to the same statistical treatment as Salamon and Munro applied in their original study[1]. However, as a first approximation, a reduction in the strength value of the coal in the Vaal basin from 7176 kPa to 4500 kPa seems acceptable provided that this value is not used outside the range of width-to-height ratios covered by Dr Van der Merwe's study.

A matter of much greater concern is the approach adopted in the paper in determining the long-term stability of bord-and-pillar workings. The approach is based upon the observation that a certain amount of scaling takes place. This reduces the pillar width and, consequently, the pillar safety factor. It is then assumed that a pillar will most definitely fail when the safety factor is reduced to a value of 0,3. The pillar width at which the safety factor reaches a value of 0,3 is then calculated (equation [9] in the paper). In a separate investigation, an equation that describes the rate of scaling, R, of a pillar is derived (equation [10]). According to equation [10], the rate of scaling in metres per year is 0,015 $h^{3,7}$, where h is the mining height (m).

Using equation [10], the time can be calculated that is required to reduce the original pillar width to that which corresponds with a calculated safety factor (SF) of 0,3.

The following points have to be made.

1. The pillar-strength equation by Salamon and Munro[1], which forms the basis for pillar design in South African collieries, was derived from the back-analysis of bord-and-pillar workings that had been standing for several years or several tens of years. Consequently, the effect of scaling on pillar strength has been taken into account in the study.
2. Because of uncertainties in the assumptions concerning the load that acts on a pillar and the strength of a pillar, Salamon adopted a probabilistic concept for the design of coal pillars. According to his design methodology, the probability of pillar failure at a nominal safety factor of 1 is 50 per cent. In other words, half of the bord-and-pillar workings designed to a safety factor of 1 will be stable, while the other half will fail. At a safety factor of 0,6 the predicted probability of finding stable bord-and-pillar workings is 0,0066 or 6,6 pillars per thousand. On the other hand, the probability of stable bord-and-pillar workings at a nominal safety factor of 1,5 is 0,9947. This means that there exists a probability that 5,3 pillars out of a thousand pillars will fail.

   The choice of a critical safety factor, i.e. SF = 0,3, to determine the critical pillar dimension, and to use this dimension to determine the time it takes for pillar failure to occur, is totally arbitrary and without foundation, as pillar failure can take place even at nominal safety factors of more than 1. However, as pointed out above, the probability of such failure diminishes rapidly with higher safety factors.
3. In discussing the rate of scaling, Dr Van der Merwe makes the following points.

   'The scaling rate is possibly a function of several variables, some of which can be easily 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.

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> 'Correlations were sought between the rate of scaling (defined as the quotient of amount of scaling required and the 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 multiplying assumption was made that the rate of scaling is constant. Virtually no correlation was found with safety factor, pillar stress, pillar width or any combination of them. There was, however, a surprisingly good correlation with mining height.'

If equation [10] in the paper by Dr Van der Merwe is accepted, it would follow that all coal pillars, irrespective of pillar stress, pillar strength, and pillar width, would reduce to a negligible size within a short period of time. Using equation [10], the time required for a 12 m wide pillar to reduce in width to 6 m close up has been calculated for pillars ranging in height from 2 m to 8 m. According to Figure 1, a typical pillar 12 m wide and 4 m high would scale to a 6 m wide pillar in less than 2,5 years. In the case of a 6 m high pillar this time would reduce to slightly more than 6 months. Clearly, this is not supported by experience in the vast majority of our coal mines, including Coalbrook, Cornelia, and Springfield Collieries of the Vaal basin, where high coal pillars have been standing for many tens of years without excessive scaling. The applicability of equation [10] to collieries other than Sigma Colliery has therefore to be questioned.

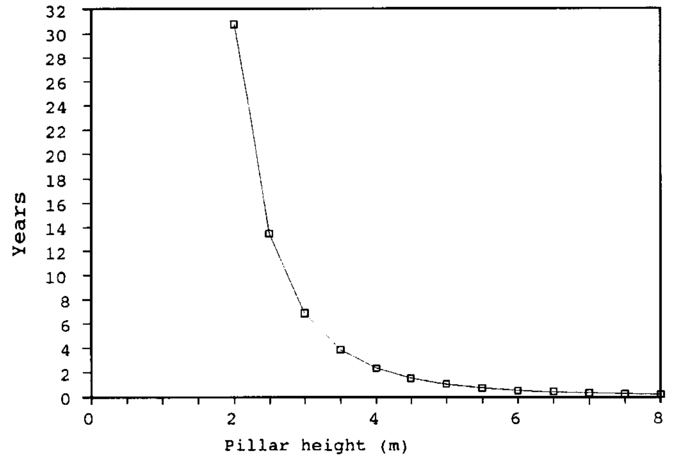

Figure 1—Time to reduce pillar width from 12 m to 6 m

SOME COMMENTS ON THE SCALING OF COAL PILLARS

The knowledge of the stress distribution in coal pillars at various stages of loading is still fairly limited. This is largely due to the difficulties of measuring stresses in coal pillars. Tests that were conducted by COMRO at Usutu colliery in the early 1970s provided some insight into the complex mechanism of load transfer from the edges of a pillar to the centre of the pillar as a result of pillar compression[2]. Figure 2 shows the complete load deformation behaviour of a coal pillar and the stress distribution in the pillar at various stages of pillar loading. Of great significance is the confinement provided to the core of the pillar by the crushed circumference of the pillar. As a result of this confinement, the core is capable of supporting stresses that are several times higher than the unconfined strength of the coal.

Recent developments in the field of numerical modelling have made it possible to model the complex process of load transfer from the periphery of a pillar to the centre as a result of yielding of the pillar circumference, which manifests itself as scaling.

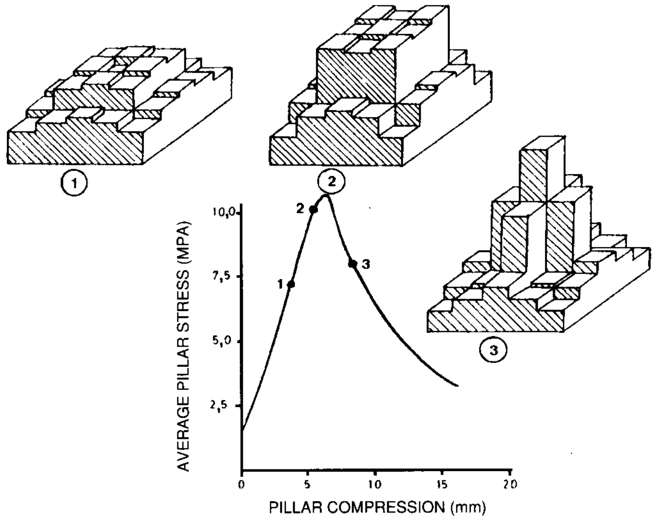

Figure 2—Stress profiles at various stages of pillar compression at a width-to-height ratio of 2 (after Wagner[2])

MODELLING OF COAL-PILLAR FRACTURING AND SCALING

A computer program known as FLAC has been used to model coal-pillar loading and to determine pillar sidewall scaling. FLAC is a two-dimensional explicit finite-difference code, which simulates the behaviour of structures built of soil, rock, or other material that may undergo plastic flow when their yield limit is exceeded. Materials are represented by elements, or zones that form a defined grid to fit the object's shape. Each element performs according to a defined linear or non-linear stress/strain relationship in response to the applied forces or boundary conditions. The code has several built-in constitutive models that permit the simulation of highly non-linear, irreversible response representative of geologic, or similar materials.

FLAC has been used successfully[3] to simulate the fracture observations recorded at Longridge colliery by Madden[4]. That study covered the behaviour of coal pillars situated at a depth of 252 m. The pillar dimensions were:

pillar width	32 m
bord width	6 m
pillar height	2,5 m.

Fracturing and scaling of pillar sidewalls was studied using a petroscope. The fractured zone was observed to extend to a depth of 1,5 m into the pillar sidewall. Figure 3 shows the calculated vertical stress profile over a distance of 6,5 m into the coal pillar. The 1,5 m deep yield zone of the edge of the pillar is clearly visible.

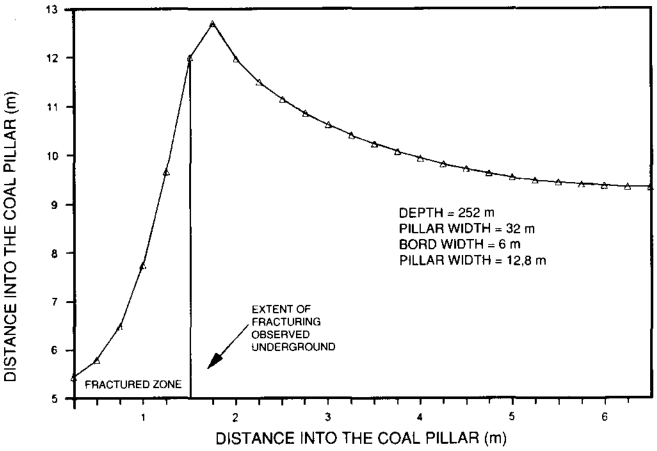

Figure 3—Vertical stress distribution and the fractured zone obtained by FLAC

The study showed that after the primary mining took place, the strength of coal at the edge of the pillar was exceeded and a yield zone developed. The fractured coal in this zone provided confinement to the core of the pillar.

In order to determine the factors that influence pillar sidewall fracturing and scaling, a set of sensitivity analyses was carried out using the following parameters:

- uniaxial compressive strength (UCS) of coal (4; 6; 8; and 10 MPa)
- Young's modulus of coal (4 GPa)
- Young's modulus of surrounding strata (6 GPa)
- interfaces, coal and the surrounding strata
    - cohesion (1 MPa)
    - friction angle (26°)
- pillar width/height ratio (2; 3; 4; and 6)
- pillar height (h = 2; 3; 4; 6 m)
- pillar width (w = 12 m)
- bord width (b = 5,6 m)
- mining depth or different loading conditions (H = 50; 75; 100; 125; 150; 175; and 200 m).

GRID GENERATION AND BOUNDARY CONDITIONS

Grid generation is used to fit the model grid to the physical region under study. In these simulations, it is assumed that the loading conditions and the geometry are symmetrical about the vertical lines that pass through the centres (pillar centre and the bord centre). The horizontal displacements on these lines will then be zero. It is also assumed that there is a horizontal symmetry line at half the pillar height, where there is no vertical displacement. Therefore only a quarter of the pillar and about 15 m of the upper strata were modelled. An artificial stress boundary was located at the top of the grid where the estimated virgin ground stress was applied.

The coal seam was divided into 0,5 m elements in the horizontal direction, and three zones in the vertical. The upper strata were represented by a coarser mesh.

THE EFFECT OF UCS OF COAL ON PILLAR SCALING

In order to determine the effect of the UCS of coal on pillar sidewall fracturing and scaling, some numerical analyses were conducted for different UCS values (4, 6, 8 and 10 MPa). Other loading conditions were kept constant (H = 100 m, w = 12 m, h = 3 m, and b = 5,6 m).

Figure 4 shows that the extent of fracturing into the pillar reduces with increased uniaxial compressive strength of the coal.

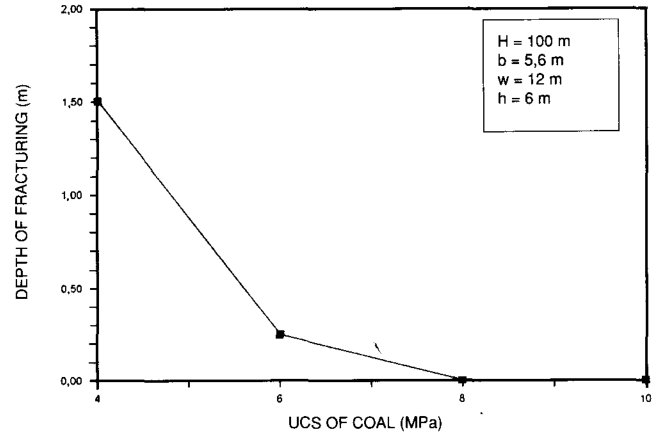

Figure 4—Effect of UCS of coal on pillar sidewall fracturing

THE EFFECT OF MINING HEIGHT (PILLAR HEIGHT) ON PILLAR SIDEWALL FRACTURING AND SCALING

Figure 5 shows that for a given set of loading conditions, the depth of the fractured zone increases with pillar height.

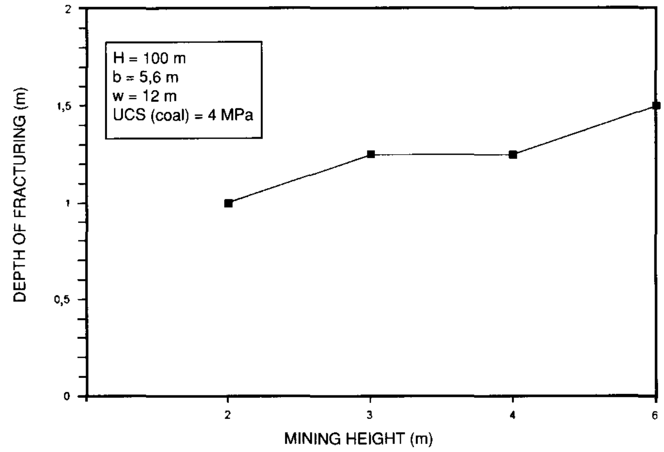

Figure 5—Effect of mining height on pillar sidewall fracturing

THE EFFECT OF PILLAR STRESS ON PILLAR SIDEWALL SCALING

In the present study, the stresses acting on the pillars were increased by increasing the mining depth in 25 m steps from 50 to 200 m. The material properties and the mining geometry were kept constant (w = 12 m, b = 5,6 m, h = 3 m).

Figure 6 shows that sidewall scaling will first take place at a depth of 75 m, with yielding of the first elements on the pillar edge. At a depth of 125 m, where the peak stress exceeds 5 MPa, the yield zone will extend to a depth of 1,5 m. At a depth of 150 m, the yield zone increases to 2,5 m, and at 175 m, the whole pillar will yield.

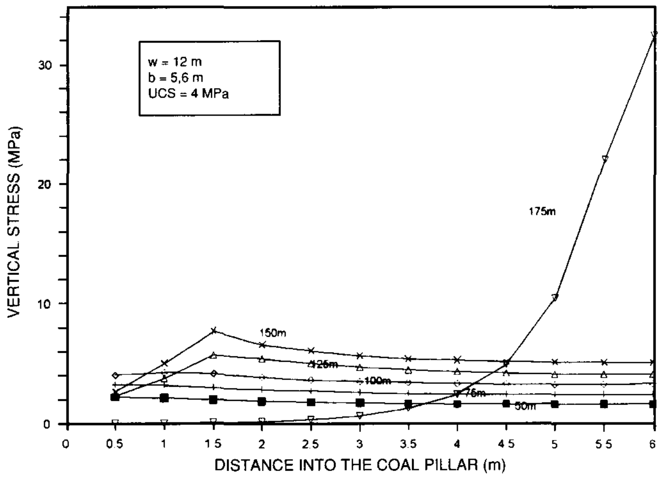

Figure 6—Effect of mining depth and vertical stresses on pillar fracturing

CONCLUSIONS

- The numerical simulations showed that the strength of the pillar material, and the stresses acting on the pillar, have a major influence on the extent of the yield zone of coal pillars and consequently on pillar scaling.
- The extent of pillar scaling under otherwise identical conditions tends to increase with pillar height.
- The methodology proposed by Dr Van der Merwe to predict the life of coal pillars on the basis of a simple relationship between the pillar height and the rate of pillar scaling cannot be supported on fundamental grounds.
- Dr Van der Merwe has highlighted the need for more detailed investigations of long-term stability of bord-and-pillar workings. This issue will become more important in the future, as the rate of urbanization in the coal-mining districts increases.

REPLY BY J.N. VAN DER MERWE

The contribution by Dr H. Wagner and Mr T.T. Ozan to my paper on coal-pillar strength in the Vaal basin is welcomed, as it a positive contribution to a very important subject.

The contribution focuses on the Pillar Life Index, which is a relative index used for prioritizing areas that require stabilization. As stated in the paper, the Index should not be used to predict pillar life for a number of very good reasons. Wanger and Ozan have added substance to the list of reasons.

I fully concur with the cautionary note that the scaling rate quoted in the paper should not be used for other areas, having been derived form empirical data. In fact, very limited data for other areas indicated that the rates for the Witbank No. 2 and 4 seams may yield indices in the region of centuries and millennia respectively, as opposed to years, or at most decades, for the Vaal basin. The data were too scattered to yield correlation co-efficients that could justify publication, so those other scaling rates were left out of the paper. However, it remains interesting that there is some indication, however vague, that the 'stronger' areas should exhibit much slower rates of deterioration than the known 'weaker' areas. It also remains interesting that the Vaal basin failures occur at much younger ages than pillar failures elsewhere. This fact is shown in Figure 2 of the original paper. There remains justification for attempting to express pillar stability in terms of time rather than as a ratio. In my opinion this is a central principle that deserves further debate.

As a rock-engineering practitioner, I would feel much more at ease expressing the stability of underground pillars in terms of years, decades, centuries, or millennia rather than as a ratio of strength to load—both of which may change over time. This is the central issue, not the validity of an index to predict the time of failure. The paper does not claim this validity, but in fact warns against it.

As far as the fundamental basis for the use of a scaling rate to predict pillar stability is concerned, it rests on the assumption (based on observation and widely accepted) that pillar failure is preceded by scaling. In the absence of anything better, it was postulated that a pillar will scale to total destruction. If other data had been available, a different basis would have been used and a different rate or correlation, with a more understandable set of parameters, many have been found.

However, I believe that incremental improvement is better than delayed perfection, and therefore used the Pillar Life Index only as a means of prioritizing action in a practical situation on a real mine. The time of failure did not correlate with any other commonly used parameter (such as safety factor, load, strength, pillar width, depth, etc.).

It is hoped that someone may come up with more rational procedure, to explain the current one.

It should be noted that the issue taken up by Wagner and Ozan is the *rate* of scaling. In their contribution, however, they focus on the *extent* of scaling. The observations by Madden are not disputed, but it should be realized that the observations were made at an instant in time, and there is no evidence that the extent of scaling had stabilized.

The use of FLAC to investigate the extent of scaling is not disputed either. However, the essential difference between a pillar modelled by FLAC and a real pillar underground is that the real pillar's scaled exterior falls away (at least initially), thereby changing the shape of the pillar and consequently creating a new situation. In FLAC, the scaled debris remains part of the pillar, contributing to the stabilizing horizontal stresses in the pillar. Correct modelling of pillar behaviour with any model using the concept of a continuous medium thus requires the manual removal of parts of the pillar.

The difficulty, of course, is in deciding how much to remove. This means that, for the moment at least, there is a certain amount of subjectivity in modelling coal-pillar behaviour.

That the magnitude of pillar loads governs the *extent* of scaling into a pillar is not in dispute. What the empirical method could not show was a usable relationship between the *rate* of scaling and pillar load.

This does not mean that the extent of scaling is unimportant. I agree that it is vital, as any empirically deduced rate depends on the assumed depth of scaling.

Let me repeat that the paper lays no claims to perfection regarding the scaling rate. In the light of several simplifying assumptions, which had to be made due to the pressure of time in a real-life situation, the paper warns that the rate should be used only as a relative index for the purpose of prioritization. Nonetheless, it must be possible to relate stability to time. This is the issue that has to be pursued.

Perhaps more efforts should be made to use Barron and Pen's[5] model of crush-yield-elastic zones inside a pillar to determine a realistic depth of scaling, and consequently derive a more dependable rate.

If one compares the quantity of data, computing capabilities, and number of trained rock engineers available in the 1960s to those of today, then the researchers at that time can be excused for not addressing the issue of the time dependency of failure. We cannot be excused.