Verification of pillar life prediction method

by J.N. van der Merwe*

Synopsis

The principal goal of the research described in the paper was to determine, by measurement of pillar scaling on pillars that have not failed, whether the pillar life prediction method developed by van der Merwe (2003) was valid as it stood or whether adjustments were necessary to the rates indirectly derived from observation of failed pillars.

To this end, measurements were taken on over 350 pillars at 13 sites on 6 mines. The project was done as a collaborative effort between the University of Pretoria, the Nancy School of Mines and CSIR Miningtek.

During the course of the investigation, it was found that the majority of pillars display maximum scaling at mid height, that there was no clear preferential direction of pillar scaling, and that pillar corners do not scale significantly more than the mid pillar areas.

The most important conclusion was that the scaling rates found by measurement agreed with the inferred rates found in the previous work. The previously developed procedure for the prediction of pillar life spans consequently requires no adjustment, although the error span is in the region of 20%.

It is recommended to do further research into the effect of sealing of panels and, possible chemical changes taking place in the pillars as they age on the scaling rate.

Introduction

During the period 2000 to 2001, a procedure to predict coal pillar lifespans based on the observation that coal pillars fail by a process of progressive scaling, was developed (van der Merwe, 2003).

The procedure was based on the observation that all pillars scale and that, only in isolated cases, did pillars fail immediately. It was then concluded that at the time of failure, pillars were smaller than at the time of mining. It was postulated that there was a certain minimum size, corresponding to a mininum safety factor, at which a pillar had to fail, and that failure only occurred when that certain minimum safety factor had been reached. As there were no data available on what the actual pillar dimensions were at the time of failure, the minimum safety factor could not be known. An assumption was then made, namely that that minimum safety factor would be the lowest safety factor of any pillar in the database of failed pillars. This was found to be 0.4, using the linear pillar strength formula of van der Merwe (2003a).

The next step was to calculate the distance by which the pillar widths in the database of failed pillars had to be reduced to reach the minimum safety factor of 0.4. This was termed the scaling distance. As the lifespans of the pillars in the database were known, the rate of pillar scaling could then be calculated. This formed the basis of the pillar life prediction method.

There are two certainties in the sequence of this argument, namely the pillar dimensions at the time of mining and the elapsed time between the creation of the pillars and their eventual failure. In between these two points, the scaling rate is linked to the assumption of the minimum safety factor, as the minimum safety factor determines the scaling distance that is required to result in failure. For instance, if the real minimum safety factor is greater than the assumed value of 0.4, then the scaling distance would be smaller and the rate also lower, because the age of the pillar at the time of failure is fixed. Conversely, if the minimum safety factor is less than 0.4, then the real scaling distance would be greater and the rate consequently higher.

This would not have a dramatic effect on the pillar life prediction, as any change in the real minimum safety factor would be compensated for by an accompanying change in the scaling rate. Nonetheless, it remained an unproven assumption in the procedure.

The assumption could be proven by direct measurement of either one of the two

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unknowns, i.e. the real minimum saftey factor or the rate of scaling, as they are linked. The real pillar dimensions at the time of failure could not be measured, but the rate of scaling of existing intact pillars, prior to failure, could be determined.

This paper describes an investigation into the rate of scaling by measuring the amount of scaling of pillars of which the original dimensions could be determined and of which the time of mining was known.

Method of measurement

The measurements were taken by Mr Christophe Baron, final year engineering student at the Nancy School of Mines in France, assisted by Mr Gary Prohaska of CSIR Miningtek. The data was supplemented by measurements that were taken by the mine surveyors and staff of the Department of Minerals and Energy at the Leeuwfontein Colliery.

Due to the differences in pillar shapes after some scaling had occurred, it was necessary to decide where the measurements should be taken—mid height, position of maximum scaling, etc. This decision was based on observation and is covered in the paper.

It was also necessary to determine whether there were preferential scaling directions, and therefore it was first necessary to measure all around the pillars to determine if there was a preferential direction. This aspect is covered in the paper.

The other issue was to decide how to handle the pillar corner scaling, as it has often been observed visually that pillar corners are more prone to scaling than the mid span areas. This is also addressed in the paper.

There were two methods of measurement. One was to determine the original position of the pillar edge by direct observation of, for instance, CM pick marks in the roof. The other was to measure the road width. Where road widths were measured, the new dimensions were compared to the original pillar offsets obtained from the mine survey departments or measured directly from survey plans.

It is known that pillars in the centres of panels are subjected to higher loads than ones at the edges where they are protected by the larger inter-panel pillars and therefore care was taken to obtain measurements over a representative spread of the areas.

Measurements were conducted at 13 sites on 6 mines in the Secunda and Highveld coalfields. The No. 2 and No. 4 coal seams were investigated, 3 on the No. 2 Seam and 10 on the No. 4 Seam. More than 1 800 measurements were taken.

Table I

Characteristics of data collection areas

Mine	Area	Seam	Mining method	Year of mining (m)	Air Way	Original height (m)	Original road width (m)	Pillar centers (m)	Mining depth (m)
Blinkpan		2	D&B	1963	Intake	2.92	6.03	20*20	
Delmas	Open	2	D&B	1983	Intake	2.80	6.80	17*17	94
	Sealed	2	D&B	1983	Sealed	3.00	6.78	17*17	94
Matla	A1	4	CM	1980	Intake	3.85	6.37	17*17	73
	E	4	CM	1997	Return	3.93	6.79	17*19	72.6
	G	4	CM	1981	Intake	3.96	7.14	17*20	72
	Last	4	CM	1988	Intake	3.25	6.32	17*17	70
	Q	4	CM	1997	Return	4.00	7.05	17*19	71
	T	4	CM	1996–1997	Intake	4.03	6.24	20*30	72
	U1	4	CM	1979–1980	Return	4.86	7.19	17*16	77
Secunda		4	D&B	1989–1990	Intake	2.58	6.19	28*28	169
Tweefontein		4	D&B	1980–1981	Intake	2.88	6.02	17*17	51.8
Leeuwfontein		4	D&B	2002	Intake	3.48	6.83	14*14	43

Table II

Summary of measurements taken

Mine	Area	No. of measurements	No. of pillars measured	No. of road width measurements	No. of mining height measurements
Blinkpan		207	33	69	69
Delmas	Open	185	25	75	12
	Sealed	78	10	38	49
Matla	A1	192	24	57	57
	E	240	30	51	49
	G	18	5	5	4
	Last	111	14	18	18
	T	63	30	15	9
	U1	41	19	13	7
Secunda		165	33	51	51
Tweefontein		483	73	142	26
Leeuwfontein		281	56	212	69
Total		2547	352	746	420

The areas where observations were taken are shown in Table I and the measurements in Table II. It was shown by van der Merwe (2003) that the No.2 and 4 Seams were sufficiently similar to be treated as one group.

The measurement instruments were a handheld electronic device with an accuracy of 1 mm over a distance of 10 m and survey tapes.

Observed pillar shapes

Some examples of pillar shapes after scaling are shown in Figures 1 and 2.

It was soon seen that (*e*), in other words maximum scaling at mid height, represented the most common shape. Shapes (*b*) and (*c*) occurred where obvious planes of weakness were present in the coal, while (*d*) occurred where prominent slips dominated the pillar failure mode. Shape (*a*) was not common, although it was observed. The decision was then taken to take all measurements at mid height unless the pillars were severely distorted into another shape.

Preferential scaling directions

Scaling distances were measured all around the pillars at 12 of the sites to determine whether there was a preferential scaling direction. The results from 182 pillars are summarized in Table III.

Note that in Table III, there is no reference to the age of the pillars studied or anything other than just the total amount of scaling on different sides of the pillars. It indicates that there are no significant differences.

As a consequence, the data-gathering exercise could be simplified, as it was clear that scaling measurements taken on one side of a pillar could be transferred to the other sides without appreciable error.

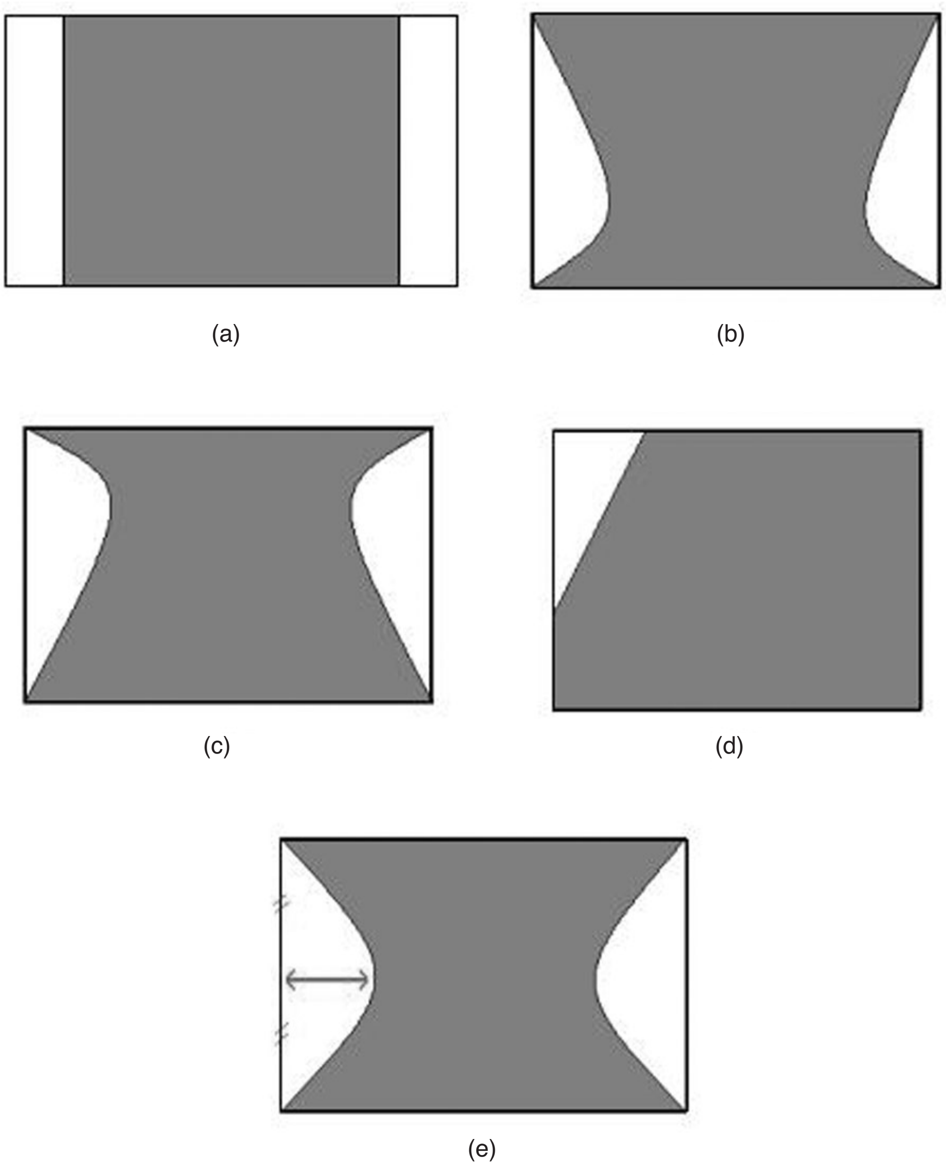
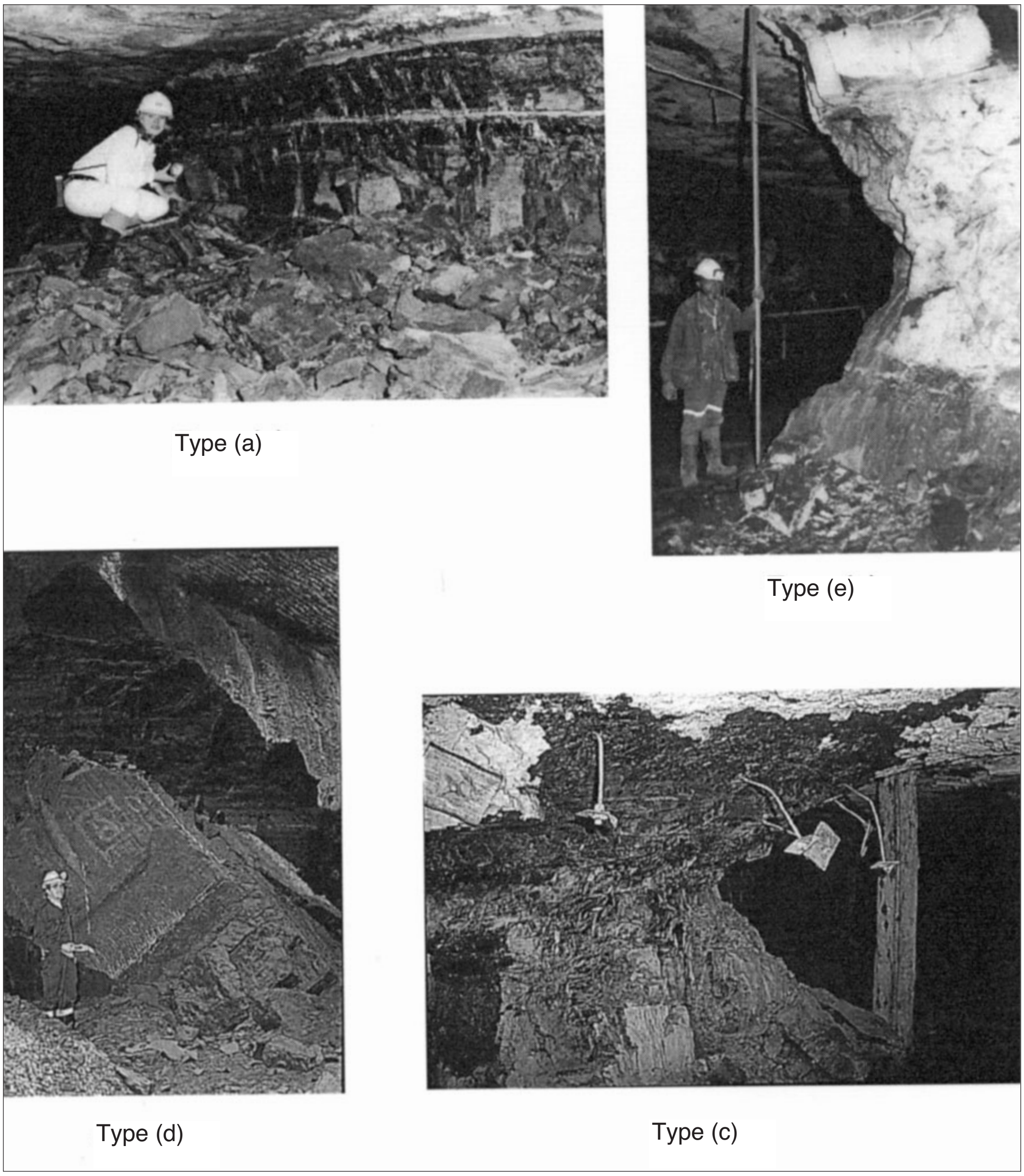


Figure 1—Examples of post-scaling pillar shapes



Type (a)

Type (e)

Type (d)

Type (c)

Figure 2—Underground examples of the basic pillar shapes shown in Figure 1. Type (e) is the most common shape

Table III

Scaling distances on different sides of pillars

		Average sidewall scaling (m)			
		North	East	South	West
No. 2 seam	Blinkpan	0.460	0.380	0.380	0.460
	Delmas—open	0.330	0.330	0.330	0.320
	Delmas—sealed	0.720	0.650	0.750	0.710
Average No. 2 seam		0.503	0.453	0.487	0.497
No. 4 seam	Matla—A1	0.510	0.505	0.480	0.490
	Matla—E	0.220	0.265	0.265	0.220
	Matla—G	0.705	0.815	0.580	0.470
	Matla—Last	0.290	0.330	0.300	0.260
	Matla—T	0.450	0.435	0.480	0.495
	Matla—U1	0.570	0.585	0.625	0.610
	Secunda	0.310	0.390	0.360	0.380
	Tweefontein—1	0.390	0.410	0.430	0.410
	Tweefontein—2	0.270	0.290	0.300	0.280
Average No. 4 seam		0.413	0.447	0.424	0.402
Average all pillars		0.435417	0.44875	0.44	0.425417

Pillar corner scaling

It has often been seen that pillar corners are more prone to scaling than the mid pillar areas. The question that had to be answered was whether this was an illusion caused by visual observation, or whether it was real, and if real, how much additional scaling occurs at the corners?

The method of investigation employed in this instance was to take direct measurements of the pillar corners and to compare them with the scaling of the sidewalls, as shown in Figure 3.

Logically, the pillar corners are more highly stressed than the mid pillar areas and have two free surfaces; therefore the expectation is that they should scale more than the mid pillar areas.

If there was no additional scaling at the pillar corners, then

$$d = \sqrt{s_1^2 + s_2^2}, \quad [1]$$

according to Figure 3. Table IV was constructed using the information obtained from 182 pillars that were measured. In the table, the parameter δd indicates the additional scaling at the corners, defined by

$$\delta d = d - \sqrt{s_1^2 + s_2^2}. \quad [2]$$

The symbols are used as shown in Figure 3. The scaling distances, s_1 and s_2 were taken at the mid pillar positions. It is seen that, on average, there is no significant difference between the mid pillar sidewall scaling and the expected corner scaling.

The conclusion drawn here is that the stress concentration on the pillar corners is, in general, not significantly greater than in the mid pillar areas. This is possibly due to the fact that the road widths are invariably narrower than the pillar widths and that the layouts are regular. The reason for the perception that corners scale more is not clear—it is possible that it exists because the scaling tends to begin at the corners and one is used to seeing cracks in the corners of fresh pillars.

At the corners, one visually observes the diagonal of the scaled area, which is by definition longer than the perpendicular distance one observes in the mid pillar areas.

Direct measurement vs. comparison with original offsets

It was found in 4 of the cases where the newly measured road widths were compared to the original average off-sets obtained from the mines, that the pillars had actually increased in size. This is clearly not possible. While the reason for this could not be established, it was decided not to use that data but to rely only on the direct measurements of scaling underground.

While this meant that some data were lost, there was still sufficient left to complete the analysis. The data that were retained for use in the scaling rate analysis, are summarized in Table V. The data that was used were collected from 352 pillars in 12 panels. The data used by van der Merwe (2003) for the indirect analysis comprised 19 panels on the combined Nos. 2 and 4 seams.

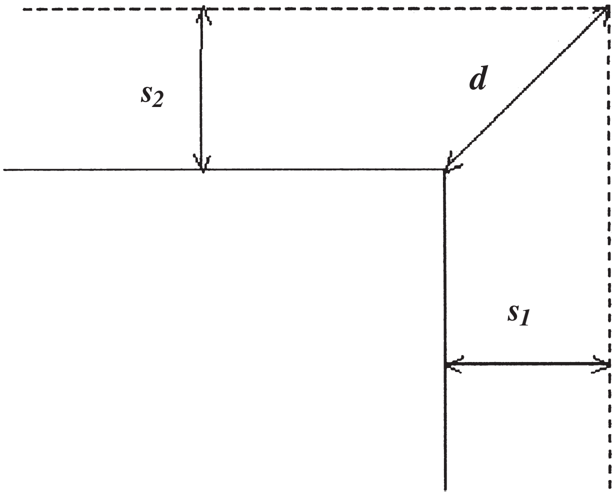


Figure 3—Measurement of pillar corner scaling

Table IV

Observation of pillar corner scaling

	Mine—area	Average of additional corner scaling δd (m)	Average of additional corner scaling (%)
No. 2 seam	Blinkpan Delmas—open Delmas—sealed	- 0.13 + 0.02 - 0.17	- 22 + 3 - 17
Average No. 2 seam		- 0.09	- 12
No. 4 seam	Matla—A1 Matla—E Matla—G Matla—Last Matla—T Matla—U1 Secunda Tweefontein—1 Tweefontein—2	+ 0.02 + 0.27 + 0.06 + 0.09 + 0.18 - 0.01 - 0.04 - 0.19 - 0.13	+ 3 + 79 + 7 + 21 + 28 - 1 - 8 - 33 - 32
Average No. 4 seam		+ 0.03	+ 7
Average all pillars		-.003	-2

Note that in the case of Leeuwfontein, the road widths were measured immediately after mining and then again 8 months later. These data were added to get direct information on the scaling rate in the early stages and to augment the database with a shallow mining case.

Table V

Data used for the scaling rate analysis

Mine	Area	Coal-seam	No. of pillars measured
Blinkpan		No. 2	33
Delmas	Open Sealed	No. 2 No. 2	25 10
Matla	A1 E G Last T U1	No. 4 No. 4 No. 4 No. 4 No. 4 No. 4	24 30 5 14 30 19
Secunda		No. 4	33
Tweefontein		No. 4	73
Leeuwfontein		No. 4	56
Total			352

Determination of scaling rates

The average scaling rates were then determined for each of the cases and compared to the predicted rate as a function of the mining height to pillar age ratio (*h*/*T*), as described by van der Merwe (2003). The scaling distances were the measured distances as shown in Table III. Note that the distances shown in Table III reflect the individual measurements taken on each side of the pillar. The scaling distance of the pillar is the sum of the scaling on opposing sides, being the total distance by which the pillar width is decreased. Table VI summarizes the results.

The average scaling rates based on the measurements, as a function of time, confirm the trends found by van der Merwe (2003), using data inferred from the ages of pillars at the time of collapse. In both cases, the maximum rate occurs in the very beginning and it then decreases sharply over a short period.

Table VI

Comparison of measured and predicted scaling rates

Mine	Area	Age (years)	Height (m)	*h/T*	Measured scaling distance (m)	Measured rate (m/yr)	Predicted rate (m/yr)
Blinkpan		39	2.92	0.0749	0.84	0.0215	0.0197
Delmas	Open Sealed	19 19	2.80 3.00	0.1474 0.1579	0.66 1.42	0.0347 0.0747	0.0342 0.0362
Matla	A1 E G Last T U1	22 5 21 14 5.5 22.5	3.85 3.93 3.96 3.25 4.03 4.86	0.1750 0.7860 0.1886 0.2321 0.7327 0.2160	1.00 0.48 1.28 0.6 0.94 1.20	0.0455 0.0960 0.0610 0.0429 0.1709 0.0533	0.0393 0.1335 0.0418 0.0495 0.1261 0.0467
Secunda		12.5	2.58	0.2064	0.72	0.0576	0.0450
Tweefontein		21.5	2.88	0.1340	0.58	0.0270	0.0316
Leeuwfontein		0.67	3.48	5.1940	0.30	0.4500	0.6204

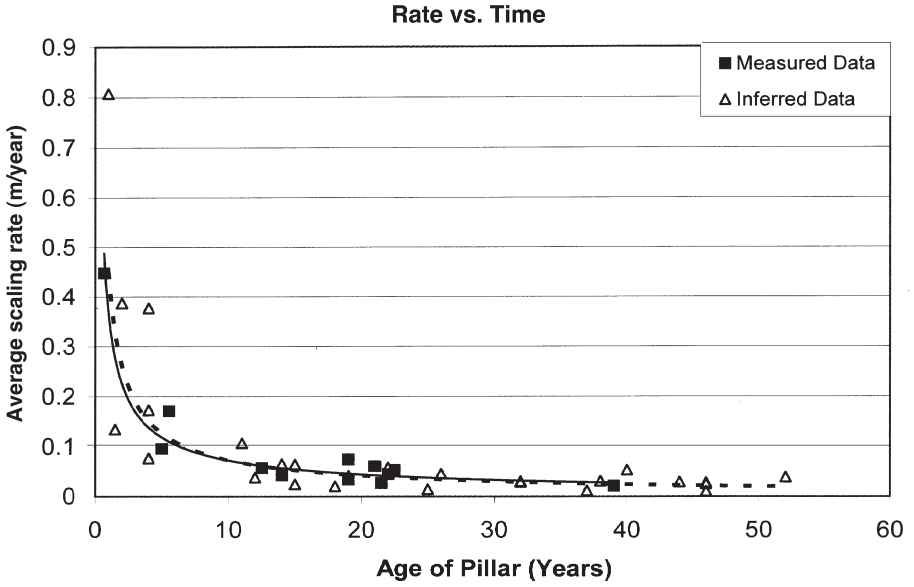


Figure 4—Comparison of the average scaling rates using the measured and the inferred data from the original paper by van der Merwe (2003)

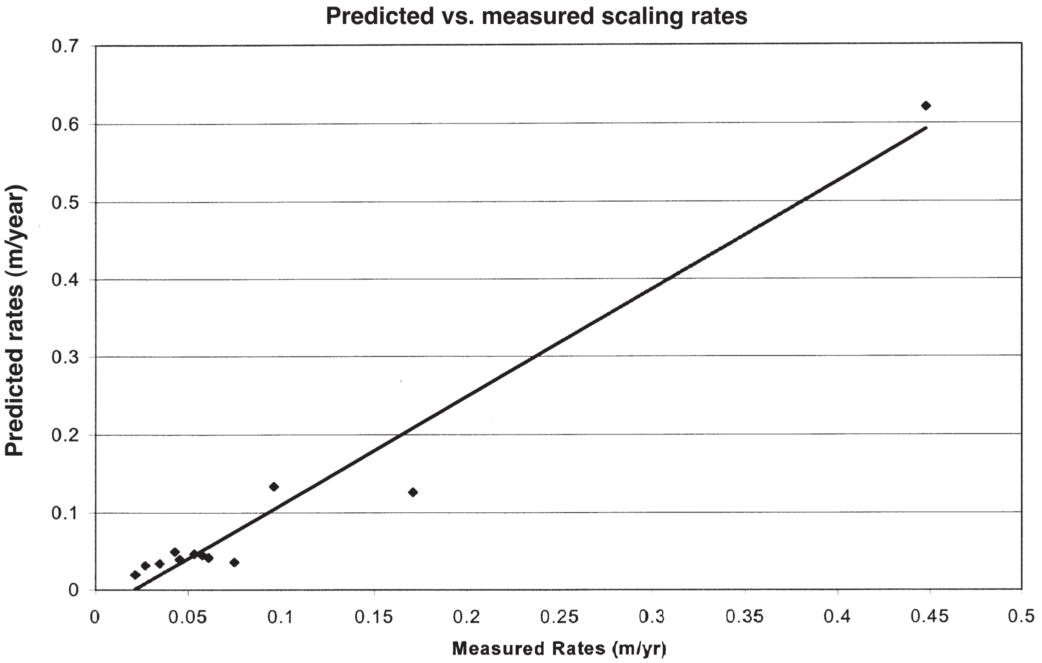


Figure 5—Comparison of predicted and measured scaling rates

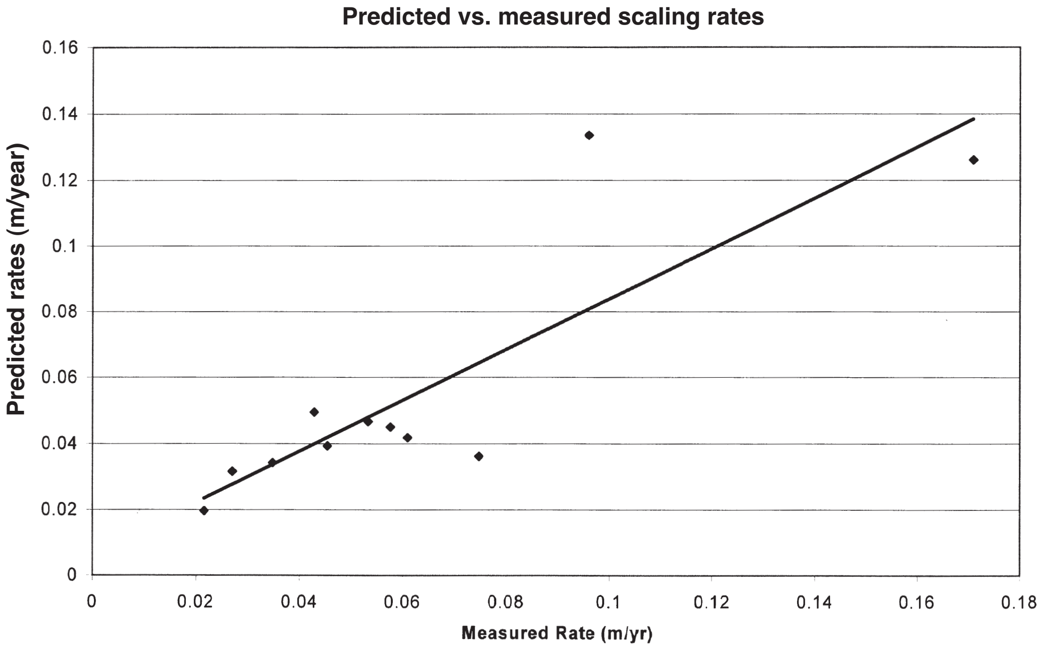


Figure 6—Reproduction of Figure 5, but excluding the single data set at the high end

This is shown in Figure 4, a comparison using the measured average scaling rates shown in Table VI and the inferred data for the Nos. 2 and 4 seams in the original paper from 2003. It is shown that the two data-sets are practically overlapping at all stages. The correlation coefficients between the measured and inferred data-sets was 0.98.

The original scaling rate, R_I, as a function of time, T, using the inferred data, was

$$R_I = 0.45T^{-0.79} \qquad [3]$$

Using the measured data, the expression is

$$R_M = 0.44T^{-0.77} \qquad [4]$$

The close correspondence between the two expressions points to the similarity of the measured and the inferred data-sets.

According to van der Merwe (2003), the prediction of pillar life is made on the basis of a scaling rate as a function of the h/T parameter. For the Witbank Nos. 2 and 4 seams, the expression for the rate of scaling was:

$$R = 0.1624\left[\frac{h}{T}\right]^{0.8135}, \qquad [5]$$

where h is the mining height in metres and T the time since mining in years.

This expression was used to calculate the 'predicted rates' shown in the last column of Table VI.

It is seen from Table VI that there is close agreement between the measured and the predicted scaling rates as a function of the h/T parameter. The correlation coefficient between the predicted and measured rates is 0.96. This could be seen as an 'inflated' correlation coefficient, due to the good agreement between the values for the Leeuwfontein case, which is a remote point on the graph (see Figure 5). Discarding that single data combination, the correlation coefficient reduces to 0.72, which is still an indication that the data are very well correlated. As a visual aid, the data excluding that data-set are shown in Figure 6 on an enlarged scale.

The high correlation coefficients can be regarded as further indication that the original assumptions and the derived scaling rates have been validated by measurement.

When the last two columns of Table VI are compared on a point by point basis, it is apparent that there is one point where the measured scaling rate is significantly greater than the predicted rate. That is the third point, from 'Delmas sealed'. It is noteworthy that the only point with a much greater than expected scaling rate—it is more than double—is also the only one where measurements could be taken in a sealed panel. All the others were ventilated. It has often been remarked by inter alia Madden (2003) that the amount of scaling appeared to increase when panels were sealed, but whether this was a perception caused by lack of cleaning-up operations or real, could never be ascertained.

A single data point is not sufficient to base any conclusion on, but it indicates a direction for further investigation.

Confidence and significance

In an empirical study, one of the most important issues is the size of the sample as, together with the amount of scatter, it affects the level of confidence that can be attached to the results.

In this particular case, the central issue is the rate of scaling, which has been seen to correspond to the predicted scaling rates with a high correlation coefficient. To test the validity of the results, standard statistical procedures were used, specifically as described by Bowker and Lieberman (1959).

For convenience, the scaling results that were found by measurement as compared to the predicted rates, are reproduced here in Table VII with the addition of the relevant statistical paramenters. The single data point from the sealed panel, 'Delmas sealed' has been omitted as it is obviously anomalous. Eleven cases are thus considered.

The hypothesis is that the ratio of predicted to measured scaling rates equals a value of 1.0; in other words that the predicted and measured scaling rates are essentially similar.

The rules for acceptance are that the type I error (i.e. the probability of rejecting the hypothesis if it is indeed true) should not exceed 5% (i.e. $\alpha = 0.05$) and the type II Error (i.e. of accepting the hypothesis if it is indeed incorrect) should not exceed 20% (i.e. $\beta = 0.2$). The maximum margin of error is 20% either side of 1.0, or the prediction should be 80% correct.

The parameter d, defined as

$$d = \frac{|\mu_1 - \mu_o|}{\sigma}, \qquad [6]$$

is then found to be 0.8 and the required sample size, n, using the appropriate standard statistical chart, is 12.

The hypothesis will be accepted if the statistic U, defined as

$$U = \frac{(\bar{x} - \mu_o)\sqrt{n}}{\sigma}, \qquad [7]$$

falls within the range $-K_{\alpha/2}$ to $K_{\alpha/2}$, or 1.96 to -1.96. As U is found to be 0.795 with values of 1.0599 and 11 for x and n respectively, the hypothesis can be accepted for the stated limits and conditions.

Conclusions

There is no clear preferential direction for pillar scaling

The data indicated that although there were minor differences in the scaling distances measured on the different sides of a

Table VII

Statistical parameters relevant to the scaling rates

Mine	Area	Measured rate (m/yr)	Predicted rate (m/yr)	Ratio of measured to predicted rate
Blinkpan		.0215	.0197	1.0924
Delmas	Open	.0347	.0342	1.0156
Matla	A1	.0455	.0393	1.155
	E	.0960	.1335	.7190
	G	.0610	.0418	1.4582
	Last	.0429	.0495	.8658
	T	.1709	.1261	1.3553
	U1	.0533	.0467	1.1424
Secunda		.0576	.0450	1.2803
Tweefontein		.0270	.0316	.8524
Leeuwfontein		.4478	.6204	.7218
Mean (μ)		.0962	.1080	1.0599
Standard Deviation (σ)		.1238	.1740	0.2499

pillar, there was no clear directional preference. Also, the differences were relatively small and not in the range likely to affect pillar stability or induce appreciable error if measurements are not taken all around a pillar. This has an important bearing on future data collection.

Pillar corners do not scale appreciably more than the sides

This rather unexpected conclusion indicates the danger of relying on visual observations that are not confirmed by measurement. The reasons for the incorrect perception that the corners are more prone to scaling are difficult to ascertain. It can be speculated that it could be because one observes the diagonal of two perpendicular scaling sets at intersections, that cracks are more visible at the corners or that the process starts at the corners. This conclusion may confirm that the pillar edge stresses are not significantly greater than the stresses deeper inside the pillar.

The pillar scaling rates previously inferred, have been confirmed by measurement within certain limits of confidence

This is the most important conclusion of the study. The central goal of the investigation was to determine whether the scaling rates inferred by the original report were correct or whether adjustments were required. Confirmation of the inferred scaling rates by direct measurement on pillars that have not failed, by implication means that the assumptions regarding the minimum safety factor of a pillar prior to failure (0.4 using the linear formula of van der Merwe 2003a), is also in the correct range. The previously developed procedure for the prediction of pillar lifespans, can thus be used with more confidence as the key assumptions have now been validated by measurement.

The limitations are that the predicted rate can only be assumed to be correct to within 80% and that there is a 20% probability of accepting an incorrect scaling rate as the correct one. These are obviously broad limits, but one has to bear in mind that there are several reasons for the amount of scatter observed in pillar behaviour.

The influence of sealing panels should receive urgent attention

It has been remarked (Madden, 2003) that once a panel is sealed off, the scaling appears to increase. It was only possible to take measurements in one panel that had been sealed and that single data point exhibited a much greater scaling rate than was anticipated. This cannot be regarded as conclusive evidence, but in the light of the serious ramifications if sealed panels do in fact have much greater scaling rates, this matter should receive urgent attention.

The mechanism of pillar deterioration should be researched

The work described in this paper focussed on the observations of pillar scaling without attempting any explanations for the phenomenon. Whether it is due to chemical changes taking place or mere material fatigue under the conditions of elevated stress and sufficient space into which to expand, remains unknown. The matter will only be fully understood once the causes are known. It is also important from the point of view of preventing pillar collapse —for instance, are pillars with higher sulphur content in the coal prone to higher scaling rates? What role does the moisture content play? How important is the oxygen level in the underground atmosphere? Are there changes in coal composition at the edges of pillars that have been exposed to the atmosphere?

These questions indicate a new direction of research into long-term pillar stability.

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References

VAN DER MERWE, J.N. A Linear Coal Pillar Strength Formula for South Africa. J. South Afr. Inst. Min & Metall. June 2003

VAN DER MERWE, J.N. Predicting Coal Pillar Life in South Africa. J. South Afr. Inst. Min & Metall. June 2003

Bowker, A.H. and Lieberman, J.L. Engineering Statistics. Prentice-Hall Inc, Englewood Cliffs, N.J. 1959. pp. 96–119.

Madden, B.J. Personal communication. 2003.

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