New pillar strength formula for South African coal

by J.N. van der Merwe*

Synopsis

The data base of failed pillar cases as used by Salamon and Munro (1967) in their original analysis to determine the strength of coal pillars empirically, has been updated for this study. It is shown that the Vaal Basin and Klip River coal fields exhibit similar behaviour that differs from the failures in other areas, i.e. failure at high safety factors within a short period of time. Those collapse cases have been omitted from the new data base. Failures in the other areas that occurred after 1967 have been added.

Using a technique to minimize the area of overlap between the populations of safety factors of failed and intact pillar cases, the new data base was re-analysed in conjunction with the original Salamon-Munro data base of intact pillar cases, from which the cases in the areas of weak coal were likewise eliminated.

It was found that a linear formula reduced the overlap area by 22%. The new formula predicts higher strength for pillars with a width-to-height ratio greater than approximately 2.0 to 3.0 and a lower strength for smaller pillars. It was also found that in order to obtain the same relative measure of stability as with the Salamon-Munro formula, the strength constant in the new formula should be within a range of 2.8 to 3.5 MPa.

For most current South African coal mining conditions, using the new formula for pillar strength will result in leaving smaller pillars without sacrificing stability. The reason for this is that the Salamon-Munro formula under-estimated the strength of larger pillars and over-estimated the strength of smaller pillars. The new formula will thus result in improved reserve utilization without sacrificing stability.

Introduction

Since 1967, the South African coal mining industry has been served well by the coal pillar design method of Salamon and Munro (1967). The formula was created in the aftermath of the infamous Coalbrook Colliery pillar collapse disaster in 1960. Since the introduction of the formula, there has not been a repetition of a collapse of that magnitude, although there was at least one close call when workers had time to evacuate a collapsing area at the Springlake Colliery in 2001.

The Salamon-Munro formula was derived empirically, making use of two data bases; one for failed pillar cases and one for stable cases. The empirical approach may be faulted for its lack of scientific explanation of all the factors that impact on pillar stability, but in a complex and variable environment, such as coal mining, it has no practical equal.

In 1965, Salamon and Munro approved 27 cases of failed pillars for inclusion in the failed data base. Since that time, additional failures have occurred. An additional 17 were identified by Madden (1995), who re-analysed the data and found a formula that was different from the original Salamon-Munro one, but not sufficiently different to warrant changing what had become a national design method.

Since 1995, still more failures have occurred and some earlier ones that had not been reported, became known. There are currently over 70 known cases of pillar collapse. It is therefore warranted to re-analyse the data to ascertain whether the strength formula of Salamon and Munro (1967) is still the best to use for pillar design.

Since it had been shown that there are distinct differences in the strength of coal pillars in some areas of South Africa, it is motivated in this paper to split the data base of failed pillars into 'Weak' and 'Normal' strength sections. The 'Normal' section was re-analysed using the statistical procedure that results in the maximum separation of the 'Failed' and 'Stable' data bases as this reduces the uncertainty to the lowest level.

The resulting pillar strength formula is linear with respect to the width-to-height ratio, corresponding with recent laboratory tests and the full size formula that was proposed by Bieniawski (1968).

It should be borne in mind throughout that in both this and the Salamon and Munro (1967) analysis, the work on failed pillars was based on the data base of failed pillars, representing less than 0.3% of the total population of pillars.

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The data base

In performing empirical analyses, the data base is of critical importance. The data base for failed cases that was used for this investigation was based on the Salamon-Munro one, with the addition of selected post- 1965 failures and the elimination of collapses from the 'weak coal areas', see next section. The data base for intact pillars was the Salamon-Munro data base, from which 9 cases originating in the same 'Weak coal areas' were likewise eliminated.

The 'Weak coal' areas

It is well known that there are areas in the country where the coal is distinctly weaker than elsewhere, even if the reduced strength cannot be quantified in all cases. The Vaal Basin is one for which the reduced strength has been quantified using empirical methods, Van der Merwe (1993). A method to distinguish between the strength of different coal samples based on laboratory strength was developed by Van der Merwe (2001), which confirmed that the Vaal Basin coal is significantly weaker than elsewhere.

Figure 1 shows the Safety Factors for all failed cases as a function of time. From that, it is seen that the Vaal Basin and Klip River Coalfield exhibit similar patterns, namely failures at high safety factors in a relatively short time, while the rest of the failures all tend to form a unified, if spread, group.

The Vaal Basin and Klip River failures were then excluded from the data base.

Addition of new failures

The original Salamon-Munro data base consisted of 27 cases of failed panels, including 3 from the Vaal Basin which were excluded from the new data base. Madden (1995) identified a further 17 cases, including 2 from the Vaal Basin which were likewise not added to the new data base.

Since 1995, a further 28 failures became known. Some occurred after 1995 while others had occurred earlier but were not reported, as there were no losses associated with the failures. Of these, 8 were from the Vaal Basin and 5 from the Klip River coal field. The remaining 15 were added to the data base.

The data base containing 54 cases of failed panels, as it was used for this analysis, is contained in Appendix A. Figure 2 shows the numbers of cases from the different coal fields. Table I lists the limits of the important parameters that are contained in the data base of failed pillar cases.

The intact data base

The data base of intact cases, was the original one created by Salamon and Munro (1967), from which 9 cases that were known to have been in the Vaal Basin (the 'Weak coal area') were eliminated. Table II lists the limits of the important parameters that are contained in the data base of intact pillar cases.

Method of analysis

For the analysis, it was postulated that in order to be optimal, the formula that is used should result in the greatest possible separation (or minimum overlap) of the safety factors in the data bases of failed and intact cases. The technique that was used, is based on the technique to predict probabilities of failure using the distributions of demand and capacity of a system.

The technique, described by Harr (1987), essentially entails calculating the area of overlap between two distributions. In this case, the one distribution was the distribution of safety factors of failed pillar cases and the other was the distribution of safety factors of stable pillar cases. The perfect

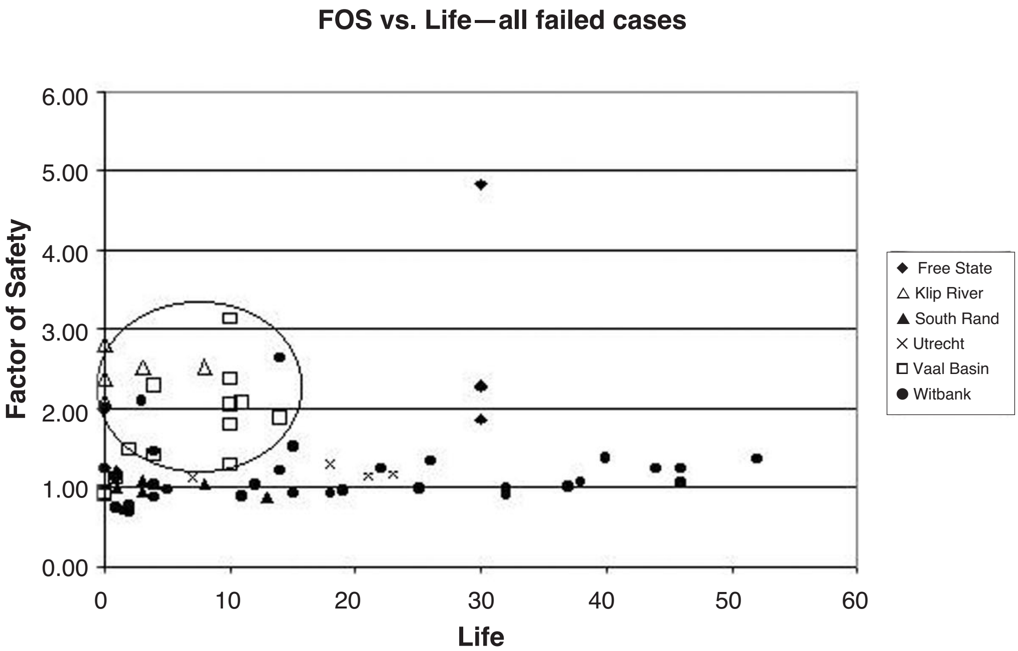

Figure 1—Failures shown as function of Safety Factor and Time, for the different coal fields

*The two Delmas samples were tested in different laboratories under different conditions

Appendix A.

Data base of failed pillars

In the following table, the prefix 's' in front of the case numbers, indicate that the data is from the original Salamon-Munro data base. Likewise, the prefix 'm' indicates that the data was gathered by Madden and 'n' that the data is post- 1995.

Case no.	Colliery	Seam	Coalfield	Depth (m)	Pillar width (m)	Bord width (m)	Mining height (m)
s9	New Largo	W4	Witbank	30.5	3.4	6.4	2.6
s67	Springfield	Main	South Rand	184.7	15.9	5.5	5.5
s66	Springfield	Main	South Rand	193.2	15.9	5.5	5.5
s64	South Witbank	W4	Witbank	61.0	4.7	6.9	3.5
s60	Coalbrook	OFS2	Vaal Basin	152.4	12.2	6.1	4.9
s59	Cornelia	OFS2	Vaal Basin	57.9	5.2	6.4	3.7
s58	South Witbank	W5	Witbank	57.9	5.2	6.4	5.5
s57	Koornfontein	W2	Witbank	88.4	7.2	6.6	4.9
s55	Blesbok	W5	Witbank	68.6	3.4	5.8	1.5
s54	Welgedacht	Springs	Springs-Witbank	62.5	6.1	7.6	2.4
s42	South Witbank	W5	Witbank	53.3	5.2	6.4	3.7
s41	Crown Douglas	W2	Witbank	30.5	4.6	7.6	3.7
s40	Wolvekrans	W2	Witbank	33.5	6.1	6.7	5.5
s39	Kendal	W5	Witbank	36.6	4.6	7.6	2.4
s19	Apex	Springs	Springs-Witbank	36.6	6.1	7.6	4.9
s18	Witbank	W2	Witbank	27.4	3.7	7.9	2.1
s17	Wolvekrans	W2	Witbank	29.6	5.2	7.0	5.5
s16	M Steam	W2	Witbank	21.3	4.0	8.2	4.6
s126	Vierfontein	Main	Free State	87.8	6.1	6.1	2.0
s122	Springfield	Main	South Rand	167.6	15.9	5.5	5.5
s120	Cornelia	OFS1	Vaal Basin	128.0	9.8	5.5	3.7
s12	Coronation	W1	Witbank	25.9	3.7	8.5	3.1
s119	W. Consol.	W4	Witbank	41.1	4.3	6.4	3.1
s118	Waterpan	W2	Witbank	57.9	6.1	7.6	4.0
s117	Waterpan	W2	Witbank	61.0	6.1	7.6	3.1
s116	Waterpan	W2	Witbank	61.0	6.1	6.1	4.6
s115	Union	Ermelo Breyten	Eastern Transvaal	76.2	4.9	6.1	1.4
n204	Vierfontein	Main	Free State	21.0	6.8	5.3	3.2
n203	Vierfontein	Main	Free State	53.0	5.6	6.1	1.8
n202	Vierfontein	Main	Free State	60.0	7.0	6.0	1.8
n201	Vierfontein	Main	Free State	29.0	5.4	6.3	2.9
n200	New Largo	W	Witbank	43.0	4.8	6.2	2.8
n199	New Largo	W4	Witbank	32.5	3.2	6.5	2.1
n198	New Largo	W4	Witbank	32.0	3.3	6.4	2.3
n196	Sigma	OFS2a	Vaal Basin	104.0	12.0	6.0	3.0
n195	Sigma	OFS3	Vaal Basin	82.0	12.0	6.0	3.0
n194	Sigma	OFS2a	Vaal Basin	96.0	12.0	6.0	6.0
n188	Umgala	Alfred	Utrecht	51.5	6.0	6.0	3.9
n187	Umgala	Alfred	Utrecht	97.0	9.0	6.6	3.7
n186	Umgala	Alfred	Utrecht	100.0	8.5	6.5	3.3
n185	Umgala	Alfred	Utrecht	101.0	9.0	6.0	3.8
n184	Sigma	OFS2a	Vaal Basin	112.0	11.5	5.5	2.9
n183	Sigma	OFS2b	Vaal Basin	88.0	11.0	6.0	2.9
n182	Sigma	OFS2b	Vaal Basin	70.0	12.5	5.5	2.9
n181	Sigma	OFS3	Vaal Basin	96.0	12.0	6.0	2.9
n180	Sigma	OFS3	Vaal Basin	82.0	10.0	5.0	2.8
n179	Ballengeigh			74.0	10.0	5.0	4.0
n173	Wolvekrans	W2	Witbank	41.0	6.4	6.4	6.2
n172	Wolvekrans	W2	Witbank	41.0	6.4	6.4	6.2
n171	Wolvekrans	W2	Witbank	41.0	6.4	6.4	6.2
m170	Springfield	Main	South Rand	205.0	17.0	6.0	5.9
m169	Springfield	Main	South Rand	195.0	17.0	6.0	4.9
m168	Springfield	Main	South Rand	165.7	15.0	5.0	5.9
m167	Tweefontein	W2	Witbank	62.0	6.1	6.1	4.0
m166	Tweefontein	W2	Witbank	62.0	6.1	6.1	4.0
m165	Springbok	W5	Witbank	22.0	3.5	6.5	1.6
m164	Wolvekrans	W2	Witbank	33.0	6.4	6.4	4.9
m163	South Witbank	W4	Witbank	56.0	5.1	6.5	3.3
m162	Tweefontein	W2	Witbank	62.0	7.3	6.2	4.0
m159	Sigma	OFS2	Vaal Basin	108.0	10.6	6.5	3.2
m157	Sigma	OFS2	Vaal Basin	112.0	10.6	6.5	2.8
m151	Tweefontein	W2	Witbank	62.0	7.5	6.4	4.0
m150	Blesbok	W5	Witbank	57.0	3.6	5.4	1.4
m149	Koornfontein	W2	Witbank	90.0	7.5	6.0	4.8
m148b	New Largo	W4	Witbank	34.0	3.5	6.7	2.7
m148a	New Largo	W4	Witbank	34.0	3.5	6.7	2.7
m148	New Largo	W4	Witbank	28.5	3.8	5.8	2.7

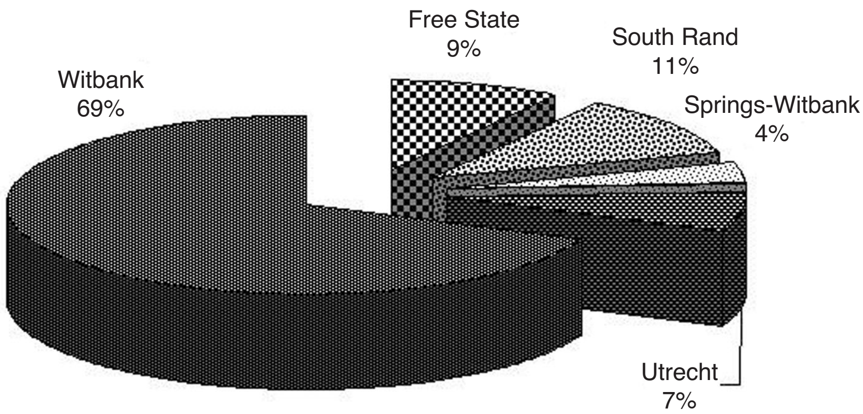

Figure 2—Localities of the cases of failed pillar cases

Table I

Limits of mining depth, pillar width, bord width, mining height and width-to-height ratio that are contained in the failed data base

	Depth (m)	Pillar width (m)	Bord width (m)	Mining height (m)	Width-to-height
Maximum	205.0	17.0	8.5	6.2	3.8
Minimum	21.0	3.2	5.0	1.4	0.9
Average	65.7	6.7	6.4	3.7	1.9
Standard deviation	47.2	3.7	0.8	1.4	0.8

Table II

Limits of mining depth, pillar width, bord width, mining height and width-to-height ratio that are contained in the intact data base

	Depth (m)	Pillar width (m)	Bord width (m)	Mining Height (m)	Width-to-height
Maximum	219.5	21.7	7.6	5.2	8.8
Minimum	19.8	2.7	3.7	1.2	1.2
Average	82.7	9.1	6.0	2.8	3.7
Standard deviation	43.0	3.7	0.5	1.1	1.8

formula would result in no overlap between these distributions. While perfection is not yet possible, the formula can be optimized by minimizing the overlap area, see Figure 3.

It is common cause that the strength of a pillar is a function of its width-to-height ratio (w/h) and a constant representing the strength of the coal material, the most common notion of the latter being that it is the strength of a cubic block of coal with dimensions of a metre.

Then,

$$\sigma = kw^{a}h^{\beta} \qquad [1]$$

Where k = constant representing the strength of the coal material
w = pillar width
h = pillar height
α,β = constants.

In the Salamon-Munro formula, k = 7.17 MPa, α = 0.46 and β = -0.66.

The Safety Factor is then simply the ratio of pillar strength to load, the latter being calculated using the Tributary Area Theory.

The method that was used, was to vary α and β between 0.2 and 2.0 in increments of 0.2. For each combination, the safety factors of the cases in both the failed and intact pillar data bases were calculated. This resulted in 100 data sets of safety factors for each of the failed and intact pillar case data bases. Then, the overlap area between the frequency distributions of the safety factors of failed and intact pillar cases for each set of data was calculated. This was then compared to the overlap area using the Salamon and Munro (1967) strength formula.

The following procedure, from Harr (1987), was used to determine the relative change in the overlap areas between failed and intact pillar cases:

$$f = \frac{M_s - M_f}{\sqrt{S_s^2 + S_f^2}} \qquad [2]$$

where M_S = Mean safety factor of the population of stable pillars
M_f = Mean safety factor of the population of failed pillars

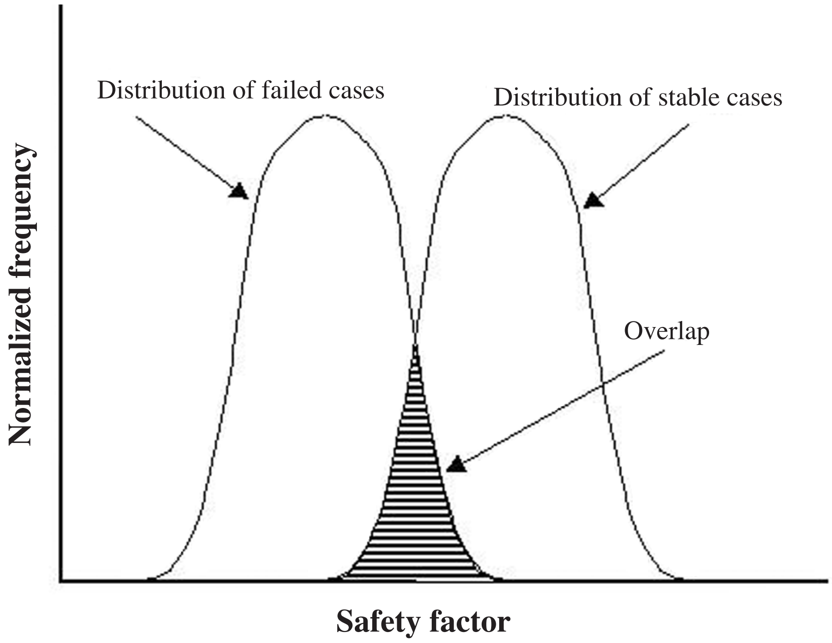

Figure 3—Concept of separating the distributions of failed and stable pillar cases

S_S = Standard deviation of the safety factors of the stable pillars

S_f = Standard deviation of the safety factors of the failed pillars.

Then,

$$\psi = 0.5 - \frac{1}{f}(2\pi)^{-0.5} \exp\left(\frac{-f^2}{2}\right) \quad [3]$$

and the overlap area between the two populations is

$$A = 0.5 - \psi. \quad [4]$$

Finally, the improvement factor, I, for each of the sets is:

$$I = \frac{A_s - A_n}{A_s} \quad [5]$$

where A_S = overlap area with the original Salamon and Munro formula

A_n = overlap area with the new formula.

It should be noted that the k-constant does not influence the overlap area, as changing it merely has the effect of shifting both the intact and the failed distributions by the same amount.

Optimizing α *and* β

The results of the investigation are shown in Figure 4. The Figure shows contours of the percentage reduction of the overlap area between the safety factors in the failed and intact pillar data bases for using different values of α and β, using the Salamon-Munro values as a basis for comparison.

It is seen that the best improvement can be obtained by using values of 1.15 and 1.2 for α and β respectively. Using these values will result in a 23% reduction of the overlap area between the data bases of failed and intact pillar cases.

However, it was seen on numerous previous occasions, including the analysis of van der Merwe (2001) and the work of Bieniawski (1968), that there is a linear relationship between the strength of a coal specimen and the w/h ratio. It was therefore decided for the rest of the investigation to adopt a conservative approach by using the linear form, i.e. α = β = 1.0. This combination results in a 22% reduction of the overlap area.

The frequency distribution of safety factors of the data sets of failed and intact pillar cases using the Salamon-Munro constants is shown in Figure 5. Figure 6 shows the same distributions, for the case where the linear constants are used. Visual comparison of the two Figures also shows the reduction of the overlap area for the case where a linear relationship is used.

Matching k to α *and* β

The constants k, α and β are inter-dependent and consequently changing one also requires changing the others. It was decided to adhere to the accepted norm that at a safety factor of 1.0, the probability of having a stable lay-out should be 0.5. The probability of having a stable lay-out from the point of view of the collapsed pillar cases, is given by the cumulative frequency distribution of the population of failed pillar cases.

Note that the real probability of having a stable lay-out is much greater, as that should be determined using all the cases of stable lay-outs at specific safety factors in comparison with the recorded cases of failed pillar cases. It is estimated that less than 0.3% of all pillars have failed—the data base of failed pillar cases thus represents less than 0.3% of all the pillar cases (a 'pillar case' in this sense refers to a panel mined with bord-and-pillar mining). As a very rough indicator, the real probability of failure (the inverse of the probability of having a stable lay-out) is therefore approximately 0.003 times the probability of failure based on the failed cases only. For simplicity, the probabilities of having a stable lay-out as referred to in this paper, reflects the probabilities based on failed cases only.

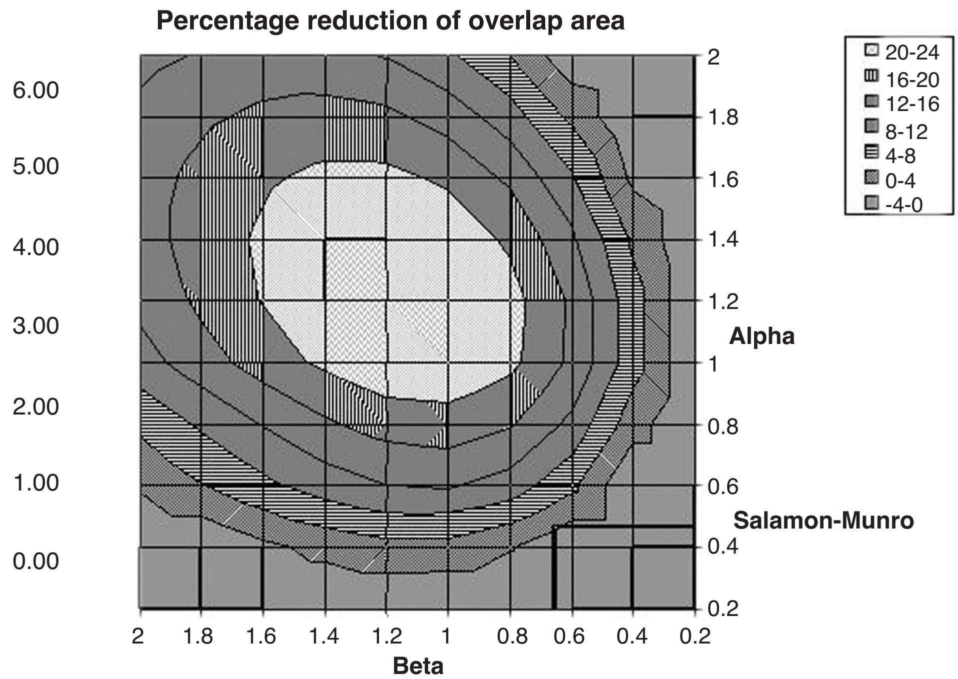

Figure 4—Contours of the reduction of overlap area between the data sets of safety factors of failed and intact pillar cases for variation of α and β

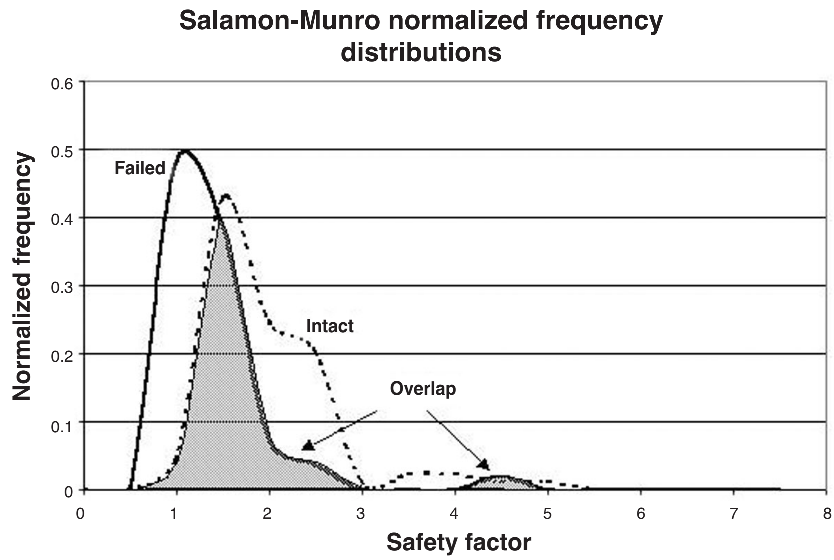

Figure 5—Distribution of the normalized frequencies of safety factors of failed and intact pillar cases showing the overlap area using the Salamon-Munro constants

Using the original data base created by Salamon and Munro (1967) with their formula, the requirement of having 50% of pillars in the failed data base fail at a safety factor of 1.0 was satisfied, see Figure 7. However, when using the extended data base with the original Salamon-Munro strength formula, it was found that the probability of having a stable lay-out at a safety factor of 1.0 is only about 0.3 or 30%. The *k*-value should be reduced to 6.5 MPa from the original value of 7.17 MPa in order to satisfy the requirement. With the adjustment, the probability of having a stable lay-out is approximately 50%, at a safety factor of 1.0. The adjusted Salamon-Munro formula will be used as a basis for comparison with the linear formula.

Once α and β have been fixed, the required value of k to result in a 50% probability of having a stable lay-out at a safety factor of 1.0 can be found by adjusting it until the safety factor of 1.0 results in a probability of having a stable lay-out of 0.5 (or 50%). It was found that for the linear relationship, the value of *k* should be 3.5 MPa. At that value the probability of having a stable lay-out is 0.5 with a safety factor of 1.0, see Figure 8. It is also seen that the distribution is almost identical to the distribution obtained by using the adjusted Salamon-Munro formula.

This implies that the probability of having a stable lay-out is the same for the linear formula with $k = 3.5$ as it is with the adjusted Salamon-Munro formula.

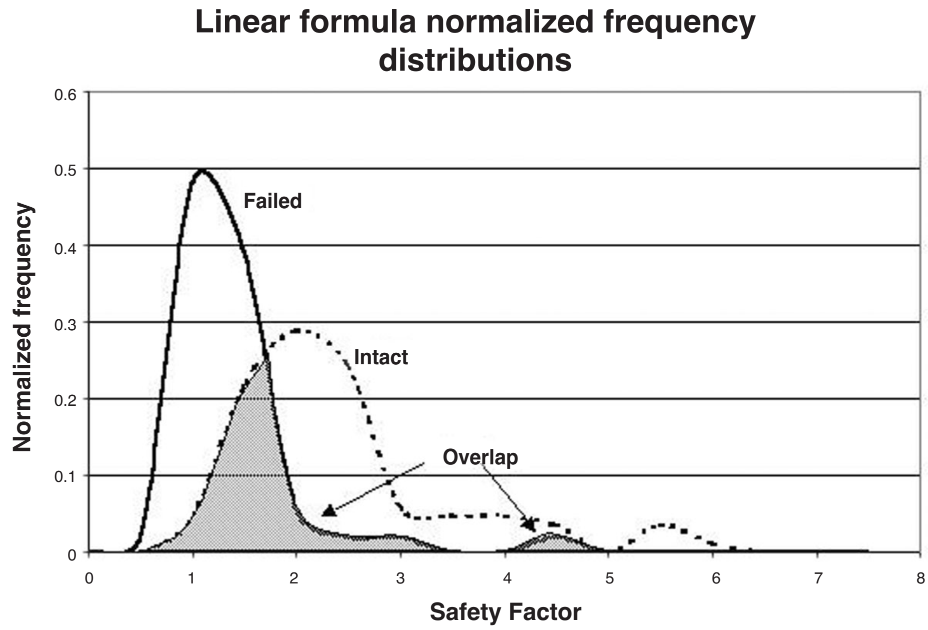

Figure 6—Distribution of the normalized frequencies of safety factors of failed and intact pillar cases showing the overlap area using the linear constants

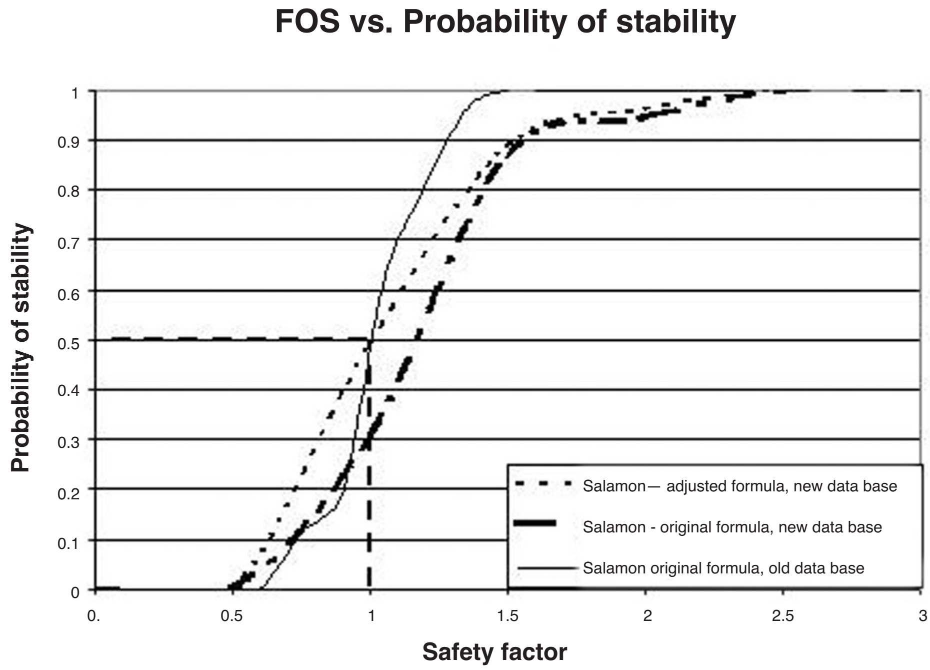

Figure 7—Probability of having a stable lay-out as a function of safety factor, for the Salamon-Munro formula

New formula for strength

Based on the foregoing, where it was shown that $\alpha = \beta = 1$ and $k = 3.5$ MPa results in the smallest overlap between the populations of failed and intact pillar cases while satisfying the requirement that a safety factor of 1.0 should imply a failure probability of 50%, it is seen that the following formula reflects coal pillars for South Africa, excluding the Vaal Basin and Klip River coal fields:

$$\sigma = 3.5\frac{w}{h} \text{ MPa} \qquad [6]$$

However, an issue that has to be addressed is the safety factor that is to be used in practical mining. The original norm that for production panels, the safety factor should be 1.6, was based on Salamon and Munro's (1967) observation that the most frequent value of safety factor in the stable data base was 1.6, see Figure 5. According to Figure 6, that value when using the linear formula is approximately 2.0. If the same norm is to be used, then the safety factor for production panels should be increased to 2.0 when the linear formula is used.

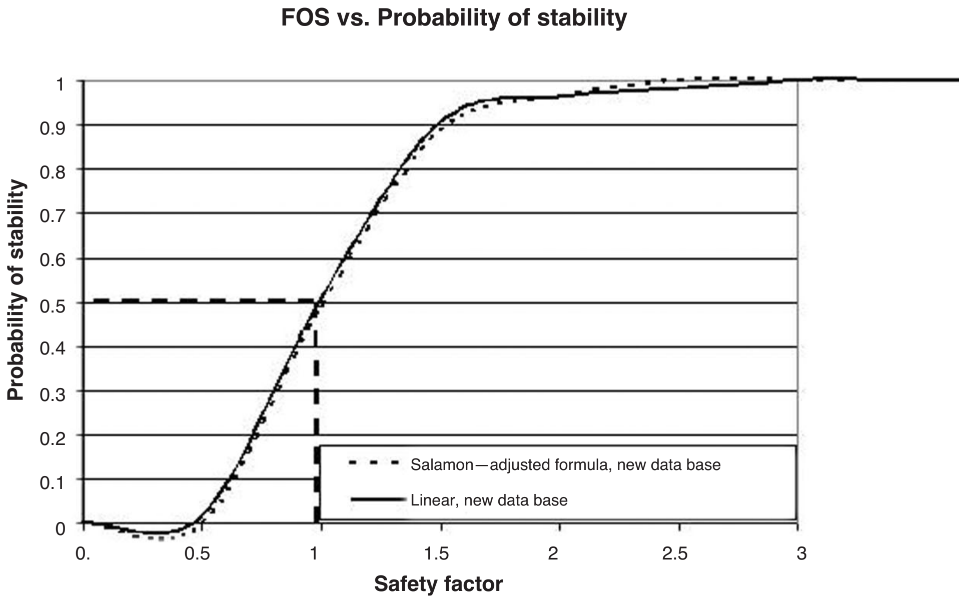

Figure 8—Comparison of the probabilities of having a stable lay-out as a function of safety factor, using the adjusted Salamon-Munro formula and the linear formula on the extended data base

However, reference to Figure 8 indicates that using either formula will result in the same measure of stability at a safety factor of 1.6. Comparison of the distributions in Figures 7 and 8 indicates that using either formula results in a lower probability of stability at a safety factor of 1.6 than was originally believed to be the case, using the limited data base of the 1960s. This implies that in order to achieve the same confidence that pillars will be stable, it is required to design to higher safety factors, no matter which formula is used. The reason for this conclusion is not because the formulae changed, but because the new data base contains double the amount of information than was available in the 1960s.

Implementing a new norm for safety factor into coal mining after more than 30 years will be a traumatic experience. It is therefore suggested, seeing that the safety factor Is directly proportional to the strength constant, or ***k***, in the formula, to rather reduce ***k*** by a factor 1.6/2.0 = 0.8 and then maintain the existing norms for magnitude of safety factor, i.e. that production panels should be designed to a safety factor of 1.6, etc. The upper limit for ***k*** should then be 3.5 and the lower limit should be 2.8 in the linear formula.

Thus, Equation [6] will be the upper limit for strength and Equation [7] the lower limit:

$$\sigma = 2.8\frac{w}{h} \qquad [7]$$

Figure 9 shows the comparison of pillar strengths for different w/h obtained with the adjusted Salamon-Munro and the lower and upper limits of the linear strength formulae. The pillar height used for this comparison was constant at 3 m.

The value of ***k***, in the range 2.8 to 3.5 MPa, that is to be used on individual mines, should be determined by local experience and controlled experimentation.

Power vs. linear format

The proposed new formula is linear, as opposed to the power format of Salamon-Munro. Much has been argued about the format of the strength formula and this issue needs to be addressed. In South Africa, the power form has been preferred, while in the USA the linear form appears to be more popular. Both have been proposed for Australia, Galvin *et al.* (1999).

There appears to be general consensus that the strength of a pillar is a function of the material strength, represented by the symbol ***k***, the pillar width, *w* and the pillar height ***h***.

The generic form for most strength formulae is given by Equation [1], repeated here:

$$\sigma = kw^{a}h^{\beta}$$

The difference in form between the different formulae, is due to the difference between the magnitudes of α and β.

In the linear formula,

$\alpha = 1$

$\beta = -1$

According to Salamon-Munro (1967),

$\alpha = 0.46$

$\beta = -0.66$.

Accounting for volume

In the strict sense of the word, both forms only account for differences in the shapes of pillars, and not for volume. It has been argued that the power formula of Salamon-Munro does account for volume. In the strict sense, however, it only accounts for volume provided that the pillar shape is not such that

$$w = h^{1.43}.$$

For all cases where $w = h^{1.43}$, the Salamon-Munro (1967) formula will predict exactly the same strength, irrespective of pillar volume.

The same argument is valid for the linear format, with different numbers. For a linear formula, it can be stated that it does account for volume for all cases except if the pillar shape is such that

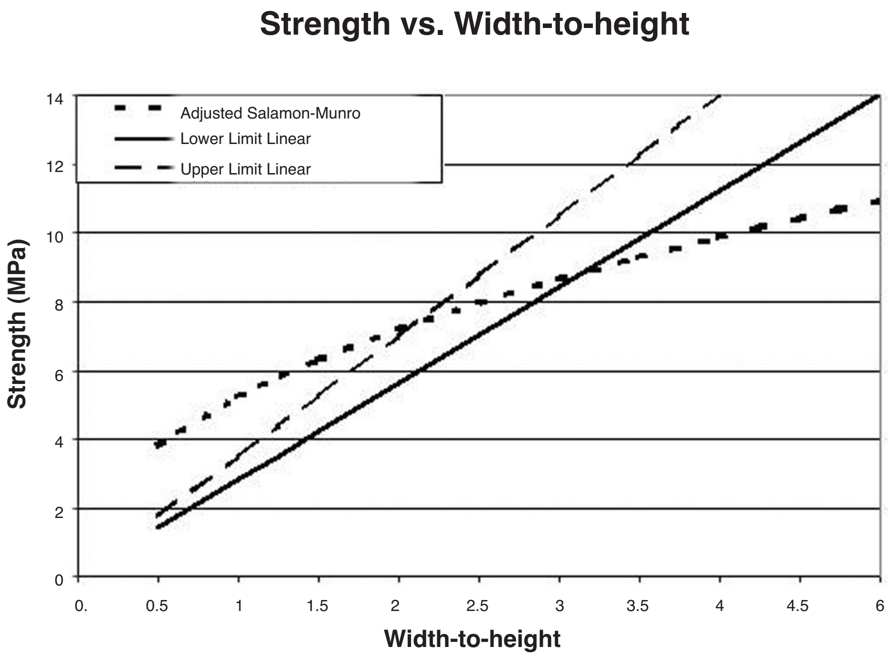

Figure 9—Comparison of predicted pillar strength, using the adjusted Salamon-Munro and the upper and lower limit linear formulae. For the comparison, the pillar width was varied while the mining height was constant at 3 m

$w = h^1$.

Either formula can be written in a form that creates the impression that it does account for volume, V, as follows—

For the Salamon-Munro power formula, after Salamon (1992):

$$\sigma = k\frac{\left(\frac{w}{h}\right)^{0.59}}{V^{0.0667}} \text{ MPa} \qquad [7]$$

The equivalent containing a term for volume in the case of the linear formula can be expressed as:

$$\sigma = k\frac{V^{0.5}}{h^{1.5}} \text{ MPa} \qquad [8]$$

However, the argument is to some extent academic. The volume consideration does not have significant effect in practice, as it has been shown several times, for instance by Bieniawski (1968) and Van der Merwe (2001), that beyond a pillar size of 1.5 m to 2 m the size (or volume) effect becomes insignificant. Real mine pillars mostly have dimensions of several metres and consequently the volume effect on pillar strength for real mine pillars can be ignored.

Strength of the weaker coal

The technique as outlined in the 'Method of analysis' section of this report cannot be used for the weaker coal areas using the same data base for the intact pillars. It would be incorrect to compare a specific group of failures in a known area of weak coal with the general intact data base, which is more suited to stronger coal areas.

Implications for industry

As shown in Figure 9, The linear formula predicts a higher strength for pillars with w/h greater than approximately 2.0 to 3.0 at a pillar height of 3 m. Figure 10 shows the difference in percentage recovery for bord-and-pillar workings with safety factors of 1.6 and 2.0 respectively, for the depth range of 30 m to 200 m,using the upper and lower limits for k. For this example, the mining height was 3 m. At other mining heights, the numbers will be different although the trends will be the same—the greater the mining height, the greater the benefit of using the linear formula. The Squat Pillar formula was used in conjunction with the Salamon-Munro formula where the width-to-height ratio of the pillars exceeded 5.0.

It is seen from the Figure that industry will benefit by using the linear formula for production panels with a safety factor of 1.6 for cases where the depth exceeds approximately 50 to 80 m, depending on whether the upper or lower limit for k is used. For a safety factor of 2.0, the benefit will start at a depth of 30 to 70 m.

Note that this benefit does not come at the cost of stability. As shown in Figure 7, the probability of having a stable lay-out for any given safety factor is for all practical purposes the same for the linear as the Salamon-Munro formula. The price is paid at shallow depth, where the pillars will have to be larger with the linear formula than when using the Salamon-Munro formula.

If South Africa produces 100 Mt of coal per year using bord-and-pillar mining at an average depth of 100 m, mining height of 3 m and a safety factor of 1.6, the Salamon-Munro formula implies a percentage extraction of 58%. This results in the sterilization of 72 Mt per year. Using the new formula will improve utilization to 62% at the average k of 3.15, which will decrease the sterilization to 61 Mt, resulting in saving of reserves of approximately 11 Mt per year, which is more than the total production of a very large mine.

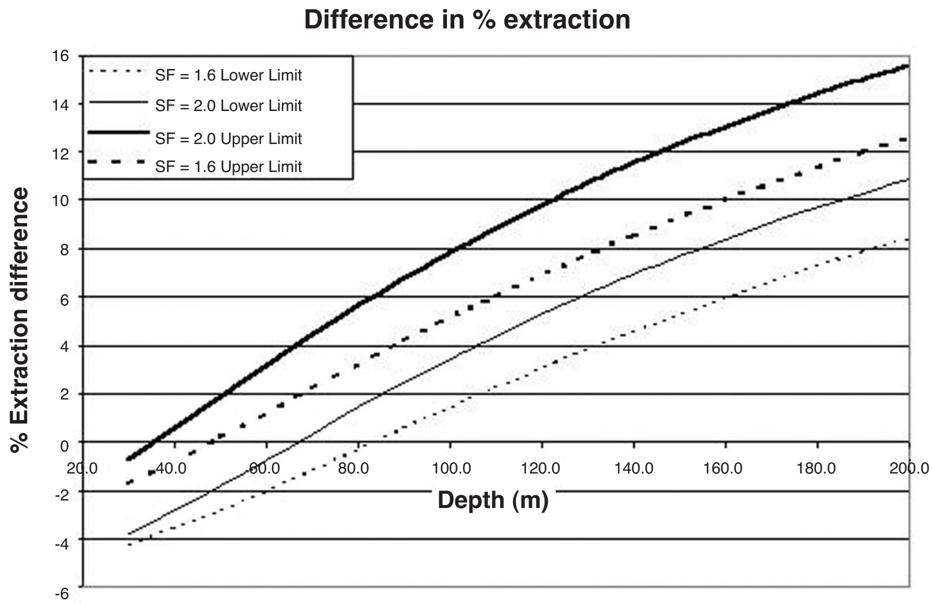

Figure 10—Comparison of recovery rates for a mining height of 3 m, at different depths and for safety factors of 2.0 and 1.6

Conclusions

Format of strength formula

It has been shown that the separation between the populations of failed and stable pillar cases can be improved by 22% by adopting a strength formula which is linear with respect to the width-to-height ratio of the pillars. It has also been shown that there are sufficiently significant differences between the groups of 'Weak' and 'Normal' coal to warrant separate analysis.

Optimum formula for 'Normal' coal

For 'Normal' coal, comprising the Witbank, South Rand, Utrecht, Springs-Witbank and Free State coal fields, the optimum strength formula is:

$$\sigma = k\frac{w}{h}, \text{with } k \text{ in the range of } 2.8 \textit{ to } 3.5 \text{ MPa}$$

This category can perhaps later be sub-divided to identify a 'Strong' coal group.

Implications for stability

It has been shown that using the linear formula results in comparable probability of having as stable lay-out as using the power formula. There is therefore no increased risk when pillars are designed using the linear formula. The balance is obtained by the consideration that at smaller w/h, the linear formula predicts lower strength and at higher w/h it predicts higher strength than the Salamon and Munro (1967) formula.

Implications for industry

It has been shown that at depth exceeding approximately 30 to 80 m, there will be a benefit with regard to the percentage extraction. At shallower depth, the percentage extraction will be less. The greater the depth, the greater the benefit and the higher the safety factor, the greater the benefit. This has important implications for situations where surface structures are to be undermined at higher safety factors.

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Appendix B

Data base of intact pillars

This table contains the original data in imperial units and the converted data to metric units

Case	Depth (ft)	Bord width (ft)	Pillar width (ft)	Mining height (ft)	Depth (m)	Bord width (m)	Pillar width (m)	Mining height (m)
1	150	17	18	6	45.72	5.18	5.49	1.83
2	70	22	20	9	21.34	6.71	6.10	2.74
4	100	18	9	5.1	30.48	5.49	2.74	1.55
5	130	20	20	8.5	39.62	6.10	6.10	2.59
6	140	18	18	8.5	42.67	5.49	5.49	2.59
6a	140	18	14	8.5	42.67	5.49	4.27	2.59
7	120	20	20	12	36.58	6.10	6.10	3.66
8	100	20	20	10.5	30.48	6.10	6.10	3.20
10	150	20	20	13	45.72	6.10	6.10	3.96
11	150	18	14	3.9	45.72	5.49	4.27	1.19
13	150	20	20	9.5	45.72	6.10	6.10	2.90
14	170	20	30	5.5	51.82	6.10	9.14	1.68
21	160	21	24	8	48.77	6.40	7.32	2.44
22	210	20.5	20	11.3	64.01	6.25	6.10	3.44
23	100	21	21	12	30.48	6.40	6.40	3.66
24	150	21	21.5	11.5	45.72	6.40	6.55	3.51
25	200	22	23	11	60.96	6.71	7.01	3.35
26	170	20	25	12	51.82	6.10	7.62	3.66
27	300	20	35	14	91.44	6.10	10.67	4.27
28	100	22	18	8.5	30.48	6.71	5.49	2.59
28a	200	22	23	8.5	60.96	6.71	7.01	2.59
29	225	18	17	3.9	68.58	5.49	5.18	1.19
31	210	25	25	10	64.01	7.62	7.62	3.05
32	200	20	25	13	60.96	6.10	7.62	3.96
33	150	20	20	5.5	45.72	6.10	6.10	1.68
34	300	20	20	5.1	91.44	6.10	6.10	1.55
35	250	18	22	9	76.20	5.49	6.71	2.74
36	150	20	16	5.4	45.72	6.10	4.88	1.65
37	200	20	16	5.1	60.96	6.10	4.88	1.55
38	280	18	27	10.5	85.34	5.49	8.23	3.20
38a	280	20	25	10.5	85.34	6.10	7.62	3.20
43	155	25	20	17	47.24	7.62	6.10	5.18
44	150	20	20	15	45.72	6.10	6.10	4.57
45	145	20	20	14	44.20	6.10	6.10	4.27
46	280	20	25	10	85.34	6.10	7.62	3.05
48	200	20	25	5.5	60.96	6.10	7.62	1.68
49	160	20	30	14	48.77	6.10	9.14	4.27
50	200	20	25	9.5	60.96	6.10	7.62	2.90
51	296	22	28	9.5	90.22	6.71	8.53	2.90
52	300	20	20	5	91.44	6.10	6.10	1.52
61	320	18	32	10.5	97.54	5.49	9.75	3.20
61a	320	20	30	10.5	97.54	6.10	9.14	3.20
62	300	18	20	3.9	91.44	5.49	6.10	1.19
63	380	20	25	6	115.82	6.10	7.62	1.83
68	356	22	25	7.5	108.51	6.71	7.62	2.29
69	356	22	28	7.5	108.51	6.71	8.53	2.29
70	150	20	20	10	45.72	6.10	6.10	3.05
72	250	20	30	13	76.20	6.10	9.14	3.96
73	300	20	40	13	91.44	6.10	12.19	3.96
74a	460	18	57	8	140.21	5.49	17.37	2.44
76	250	20	30	5.5	76.20	6.10	9.14	1.68
77	479	18	54	7.9	146.00	5.49	16.46	2.41
77a	528	20.7	49	9.7	160.93	6.31	14.94	2.96
77b	538	20.4	49.2	9.2	163.98	6.22	15.00	2.80
77c	592	19.6	50	9.8	180.44	5.97	15.24	2.99
79	450	18	42	12	137.16	5.49	12.80	3.66
80	356	21	29	7.5	108.51	6.40	8.84	2.29
82	125	18	14	5	38.10	5.49	4.27	1.52
83	135	21	21	6.5	41.15	6.40	6.40	1.98
84	720	18.3	71.3	10.4	219.46	5.58	21.73	3.17
87	350	20	40	14	106.68	6.10	12.19	4.27
88	650	18.7	56.3	9.3	198.12	5.70	17.16	2.83
89	250	20	25	15	76.20	6.10	7.62	4.57
90	600	18	52	16	182.88	5.49	15.85	4.88

Appendix B (continued)

Data base of intact pillars

This table contains the original data in imperial units and the converted data to metric units

Case	Depth (ft)	Bord width (ft)	Pillar width (ft)	Mining height (ft)	Depth (m)	Bord width (m)	Pillar width (m)	Mining height (m)
91	600	19.5	55.5	8	182.88	5.94	16.92	2.44
65	550	12.1	47	6.5	167.64	3.69	14.33	1.98
92	300	20	40	5	91.44	6.10	12.19	1.52
93	290	20	30	10	88.39	6.10	9.14	3.05
112	250	20	30	9.5	76.20	6.10	9.14	2.90
113	300	20	35	9.5	91.44	6.10	10.67	2.90
128	250	20	25	4.5	76.20	6.10	7.62	1.37
130	350	18	22	3.9	106.68	5.49	6.71	1.19
132	300	20	30	15	91.44	6.10	9.14	4.57
133	300	20	20	5.5	91.44	6.10	6.10	1.68
133a	300	20	25	5.5	91.44	6.10	7.62	1.68
134	65	20	25	10.5	19.81	6.10	7.62	3.20
135	470	18	42	5.5	143.26	5.49	12.80	1.68
136	110	18	22	13	33.53	5.49	6.71	3.96
137	380	20	30	6	115.82	6.10	9.14	1.83
138	350	20	30	5.5	106.68	6.10	9.14	1.68
142	166	20	20	4.5	50.60	6.10	6.10	1.37
143	250	20	30	4.5	76.20	6.10	9.14	1.37
144	115	16	24	8.5	35.05	4.88	7.32	2.59
145	120	16	24	6	36.58	4.88	7.32	1.83
146	150	20	25	16	45.72	6.10	7.62	4.88
146a	200	20	30	16	60.96	6.10	9.14	4.88
146b	250	20	35	16	76.20	6.10	10.67	4.88
146c	300	20	40	16	91.44	6.10	12.19	4.88
146d	350	20	50	16	106.68	6.10	15.24	4.88