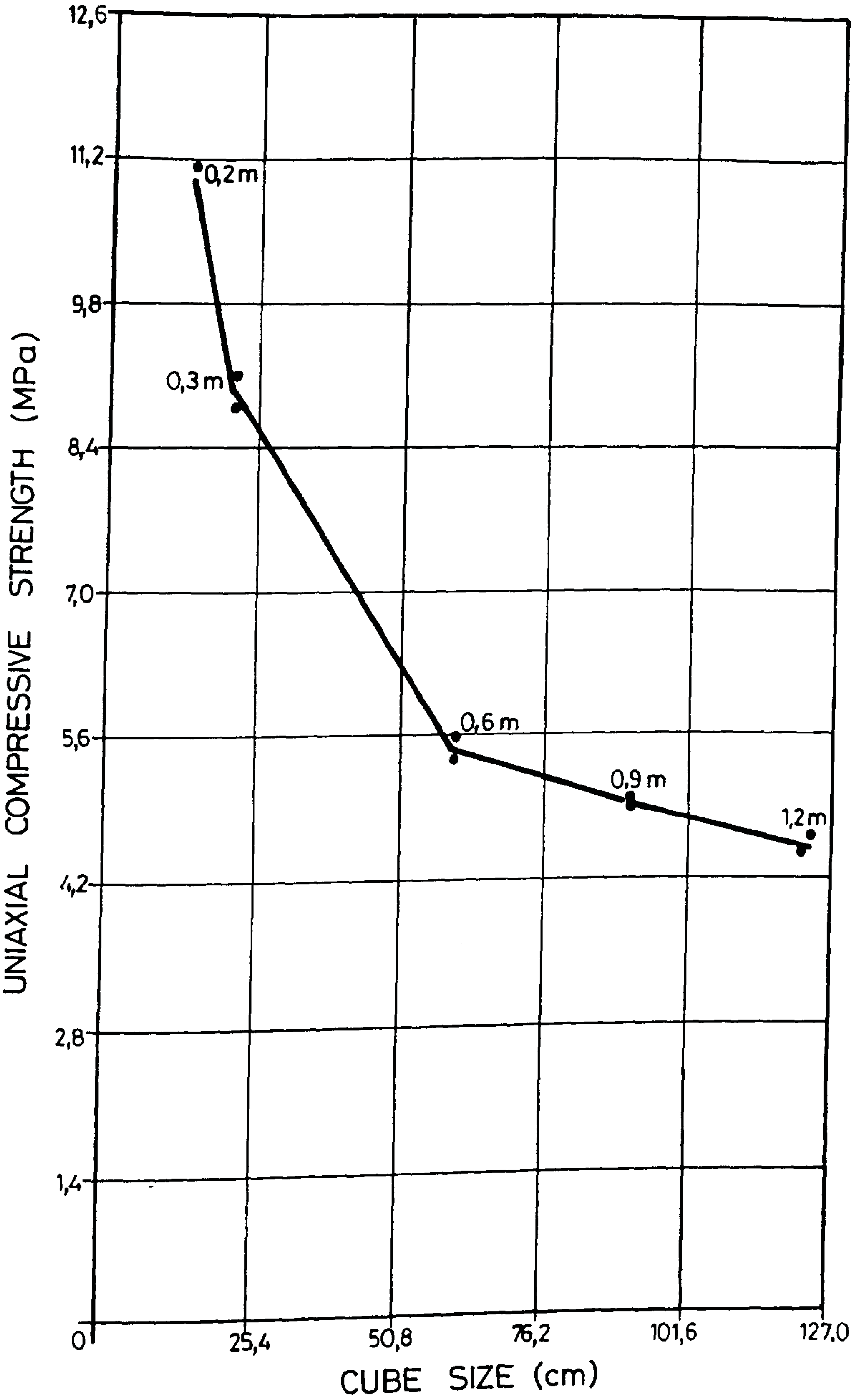

Figure 2.11 In situ stress strain curve. After Cook et. al. (1971).

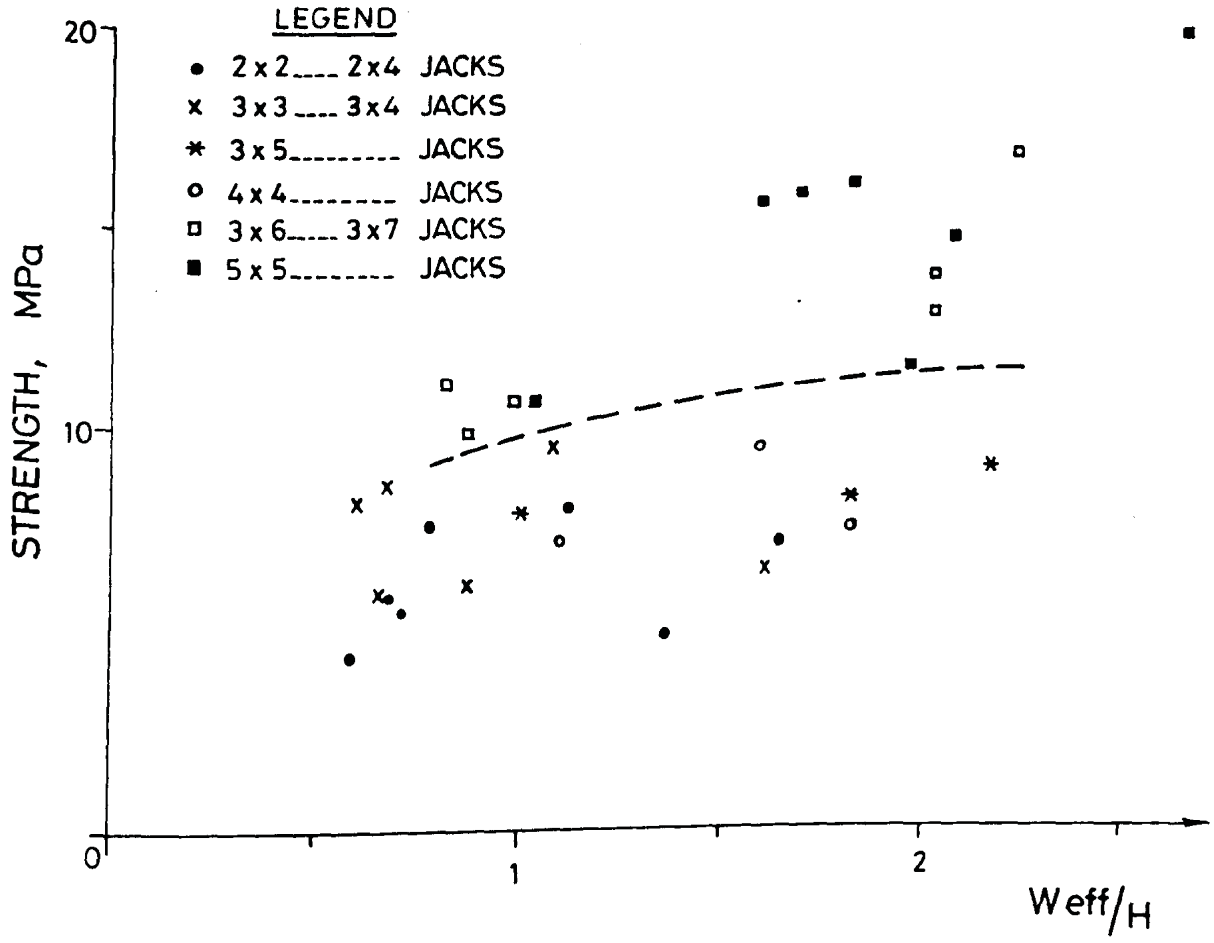

Figure 2.12 Effect of number of jacks on the pillar width to height ratio and strength of in situ specimens. After Wagner (1974).

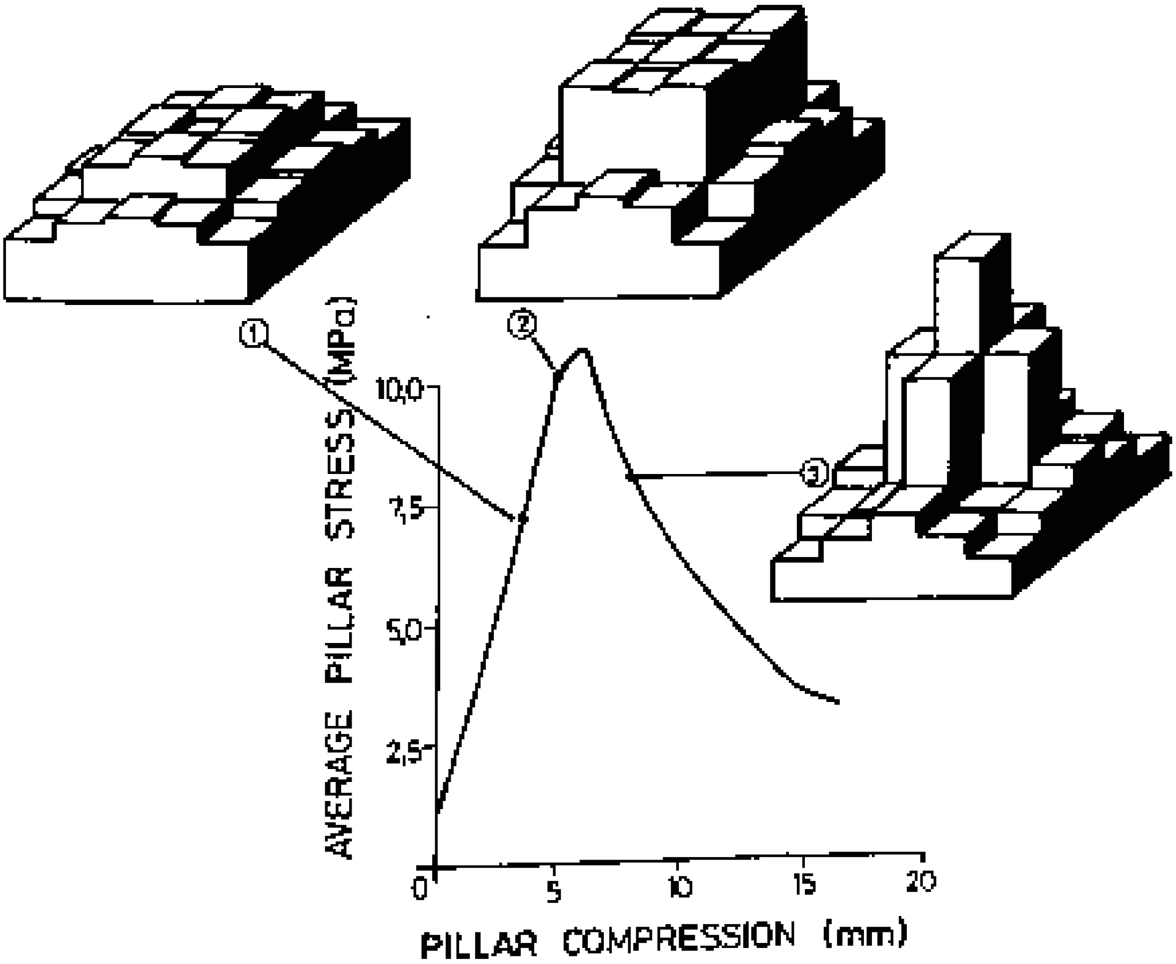

Figure 2.13 Stress in coal pillar versus pillar compression. After Wagner (1980).

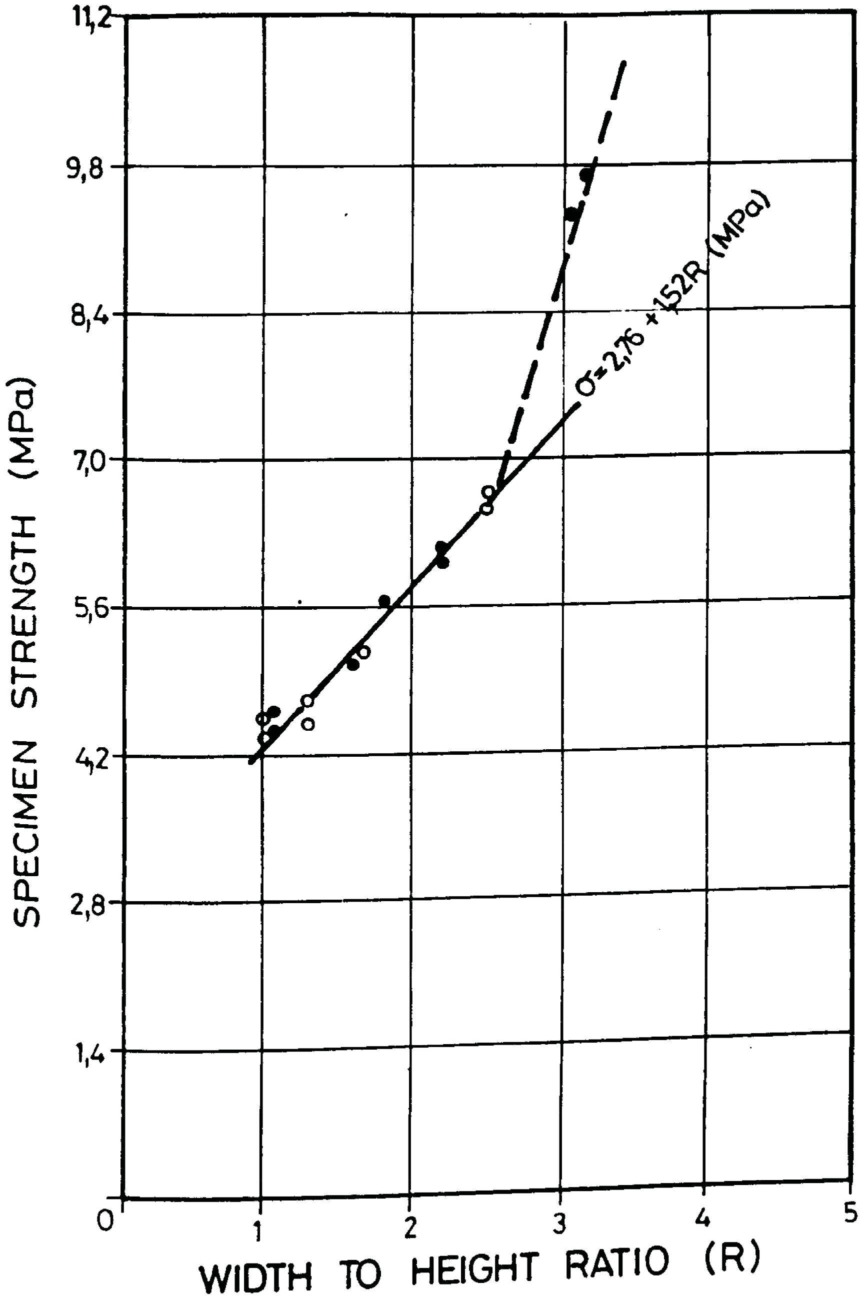

Figure 2.14 Relationship between specimen strength and its width to height ratio for square specimens at Witbank Colliery. After Bieniawski (1968e).

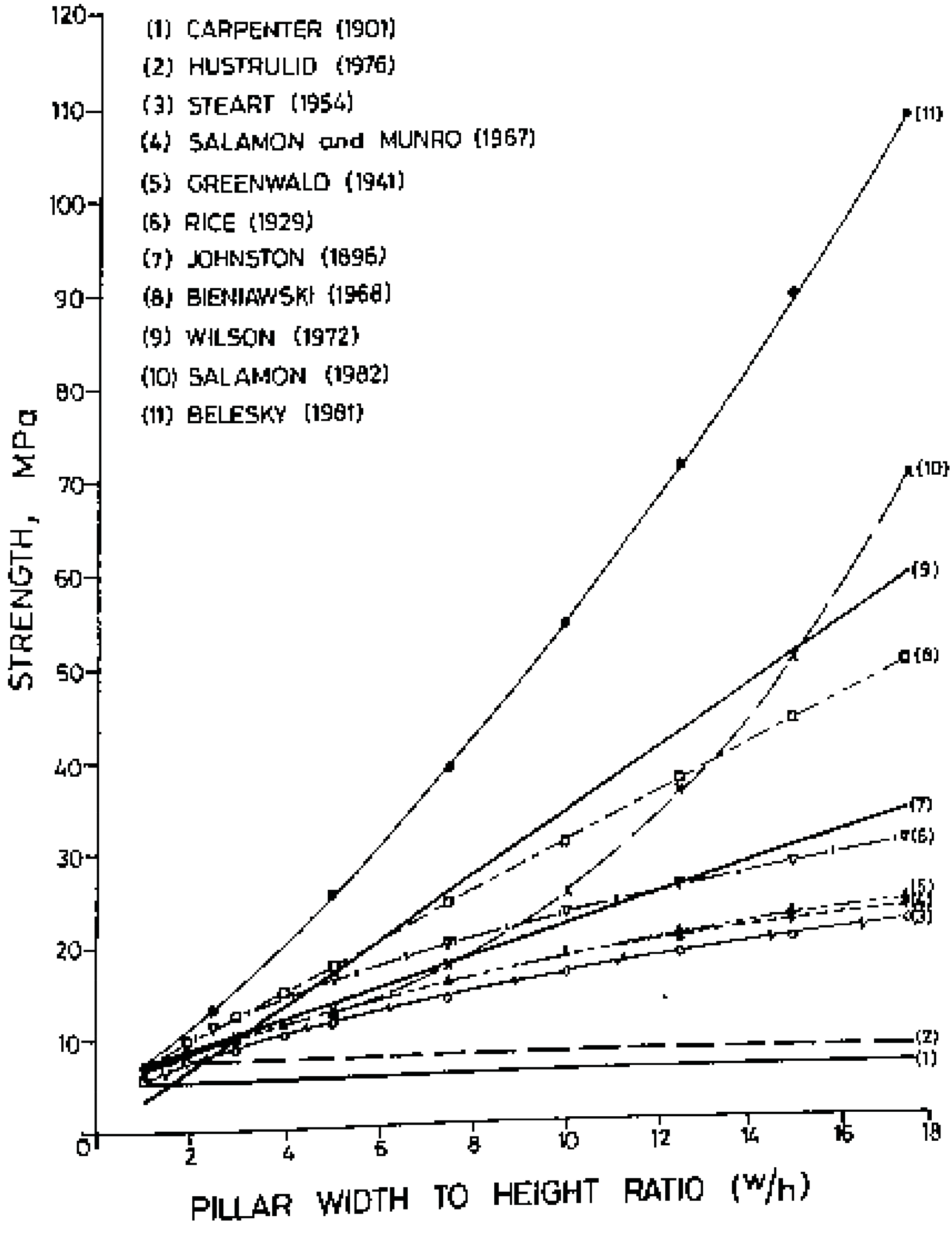

Figure 2.15 Predictive strength formula versus width to height ratio.

CHAPTER 3

REVIEW OF THE PERFORMANCE OF COAL PILLARS DESIGNED USING SALAMON AND MUNRO'S STRENGTH FORMULA.

3.1 *INTRODUCTION.*

After 22 years of application, the question must be asked, is Salamon and Munro's coal pillar strength formula still valid, considering the rapid expansion of the South African coal mining industry during this period? To answer this question coal pillar collapses that have occurred between 1966 and 1988 are reviewed in this chapter, and are compared to those used to develop Salamon and Munro's strength formula with the aim of:

i) examining the validity of applying the strength formula to South African collieries,
ii) identifying new trends with regard to the collapse of bord and pillar workings,
iii) defining limitations associated with the application of the strength formula.

3.2 COLLAPSED PILLAR GEOMETRIES.

The first report of a pillar collapse was in 1904 at the Witbank Colliery, and, up to 1965, 50 pillar collapses were recorded in the Transvaal and Orange Free State by Salamon and Wilson. These pillar collapses were examined for suitability in a statistical analysis of intact and collapsed pillar geometries, conducted by Salamon and Munro (1967), and only those cases were used where the information was sufficient and appeared to be reasonably reliable. For inclusion in the analysis the diameter of the collapsed area had to be greater than the depth below surface, and only cases with regular pillar geometries were used in the analysis. Cases where obvious bord collapse induced pillar failure were excluded as were cases where the final dimensions were unknown due to pillar robbing and pillar slyping, and where a pillar collapse occurred when two or more seams were mined in close proximity to each other. Twenty-seven collapsed cases fulfilled the criteria and were used in the statistical analysis.

The numbering system used by Salamon and Wilson (1965) has been maintained in this thesis and the dimensions converted to SI units. The record of the dimensions of the pillar geometries used in the statistical analysis conducted by Salamon and Munro (1967) has been lost and it was necessary to back calculate the dimensions. This was done by using the load and strength values of the cases plotted by Salamon (1967) and using the dimensions quoted by Salamon and Wilson (1965). Where a range of values was given for a particular parameter, the back calculation gave the most likely value that was used by Salamon and Munro (1967). By this method the pillar geometries of all 27 collapsed cases and 92 of the original 98 intact geometries were determined.

Since the introduction of Salamon and Munro's strength formula an additional 31 pillar collapses have been recorded. Information pertaining to these pillar collapses was obtained from the Government Mining Engineer's Department as part of this research investigation. In each case the Chief Surveyor of the colliery where the collapse occurred was visited and the dimensions of the collapse were confirmed. A mine plan of the collapse was also obtained.

Pillar collapses during the period 1966 to 1988 were examined with the same criteria used by Salamon and Munro (1967) to select those cases that represent pillar failure as a result of the strength of the coal pillar being exceeded by the load imposed upon it. Seventeen of the 31 cases fulfilled the criteria. Twelve Cornelia Colliery pillar collapses were excluded from the analysis as a result of the numerous and extensive roof falls that occurred in the panels. From the authors observations in a collapsed panel at Cornelia Colliery, the coal pillars contained a weak layer at the top of the coal seam. This layer readily spalls resulting in an increase in the bord width. The immediate roof consists of a carbonaceous shale and coal roof failures of up to 5,0 to 6,0 m in height have been recorded. This results in a change in the geometry of the pillar, and hence its strength, and pillar collapse results.

The remaining two collapses not included in the current analysis occurred at shallow depths of 13,5 m and 24,0 m over a very small area involving three to 11 pillars respectively, and are considered to be a result of local weaknesses in the strata.

3.3 ANALYSIS OF THE 1966 TO 1988 COLLAPSED PILLAR CASES.

Table 3.1 contains the 1966 to 1988 collapsed pillar geometries that fulfil the criteria for inclusion by Salamon and Munro. Included in the table is the seam and colliery where the collapse occurred, the pillar dimensions, date of mining (if known), date of pillar collapse, the surface area affected by the collapse and the number of pillars involved. Where an extension of a previous pillar collapse occurred, a new case number was designated. This was done to conform to the procedure of Salamon and Wilson. The 17 pillar collapses occurring between 1966 and 1988, recorded in Table 3.1, were compared with the 27 pillar collapses used by Salamon and Munro to determine any trends in the data. It should be noted that only four of the 17 collapsed pillar cases were mined after Salamon and Munro's formula was introduced.

The collapsed pillar cases for individual coal seams, that meet the requirements for inclusion in the analysis by Salamon and Munro (1967), are shown in Table 3.2. The largest group of the collapses, 34 per cent of all collapses, occurred in the No. 2 Seam of the Witbank Coalfield. This seam is the most extensively mined of all seams in South Africa. The No. 4 Seam of the Witbank Coalfield, the second most mined seam, recorded 18 per cent of pillar collapses. The seams mined in the Witbank Coalfield made up 70 per cent of the collapses and all major seams mined in the Transvaal and Orange Free State have recorded a pillar collapse.

Table 3.1 1966-1988 PILLAR COLLAPSE GEOMETRIES

Case No	Colliery	Seam	Depth (m)	Pillar Width (m)	Bord Width (m)	Mining Height (m)	Safety Factor	Date of Working	Date of Sub-sidence	Time Interval	Surface Area Affected (Hectares)	Number of Pillars	Remarks
148	New Largo	Witbank No 4	28,5	3,80	5,80	2,70	1,52	1951-53	1968	15 yrs	3,0	179	
148A	New Largo	Witbank No 4	34,0	3,50	6,70	2,70	0,92	1951-53	1968	15 yrs	3,6	312	
148B	New Largo	Witbank No 4	34,0	3,50	6,70	2,70	0,92	1951-53	1971	18 yrs	1,8	126	
149	Koornfontein	Witbank No 2	90,0	7,50	6,00	4,80	0,89	1958-59	1968	11 yrs	9,0	397	Extension of Case No 57
150	Blesbok	Witbank No 5	57,0	3,60	5,40	1,35	1,20	?	1969	?	0,65	96	
151	Tweefontein	Witbank No 2	62,0	7,50	6,40	4,00	1,37	1931	1971	40 yrs	6,3	261	
157	Sigma	OFS No 2	112,0	10,55	6,45	2,82	1,48	1975-78	1980	2 yrs	4,8	122	
159	Sigma	OFS No 2	108,0	10,55	6,48	3,18	1,41	1972-75	1979	4 yrs	18,0	1 312	
162	Tweefontein	Witbank No 2	62,0	7,30	6,20	4,00	1,36	1930	1982	52 yrs	1,8	93	Extension of Case No 166
163	South Witbank	Witbank No 4	56,0	5,10	6,50	3,30	0,96	1957	1976	19 yrs	19,5	1 256	
164	Wolverkrans	Witbank No 2	33,0	6,40	6,40	4,88	1,80	?	1983	?		56	Extension of Case No 40
165	Springbok	Witbank No 5	22,0	3,50	6,50	1,60	2,10	1982	1985	3 yrs	0,5	40	
166	Tweefontein	Witbank No 2	62,0	6,10	6,10	4,00	1,07	1930	1976	46 yrs	0,04	20	
167	Tweefontein	Witbank No 2	62,0	6,10	6,10	4,00	1,07	1930	1968	38 yrs	1,3	165	
168	Springfield	Main	165,7	15,00	5,00	5,94	1,05	1966	1970	4 yrs	5,0	106	
169	Springfield	Main	195,0	17,00	6,00	4,88	1,05	1972	1980	8 yrs	0,5	27	
170	Springfield	Main	205,0	17,00	6,00	5,88	0,88	1967	1980	13 yrs	11,9	193	

Table 3.2 Number and Percentages of Collapsed Pillar Cases Recorded in Individual Seams Meeting the Requirements for Inclusion in the Analysis by Salamon and Munro (1967).

Seam	Salamon and Munro						Total	
	Intact Cases 1965		Collapsed Cases 1904-1965		Collapsed Cases 1966-1988		Collapsed Cases 1904-1988	
	No	%	No	%	No	%	No	%
Witbank No. 5	7	7,5	3	11,1	2	11,8	5	11,4
Witbank No. 4	8	8,6	4	14,8	4	23,5	8	18,2
Witbank No. 2	45	48,8	9	33,3	6	35,3	15	34,1
Witbank No. 1	8	8,6	1	3,7	-	-	1	2,3
Springs	1	1,0	2	7,4	-	-	2	4,6
OFS No. 3	3	3,2	-	-	-	-	-	-
OFS No. 2	6	6,4	2	7,4	2	11,8	4	9,1
OFS No. 1	4	4,3	1	3,7	-	-	1	2,3
Main South Rand	1	1,0	3	11,1	3	17,7	6	13,6
Main OFS	3	3,2	1	2,7	-	-	1	2,3
Ermelo-Breyton C	6	6,4	1	2,7	-	-	1	2,3
	92		27		17		44	

Table 3.3 shows the range of parameters in the earlier study by Salamon and Munro (1967) together with the 1966 to 1988 collapses. From this table it can be concluded that there is surprisingly little variation in the parameters of the 1966 to 1988 pillar collapses compared to those of the earlier collapses.

Table 3.3 The Range of Parameters in the Original Study by Salamon and Munro (1967) as well as the 1966-1988 Collapsed Pillar Cases.

Group	Unfailed	Collapsed 1904-1965	Collapsed 1966-1988
No of cases in the group	98	27	17
Depth (H) in metres	20-220	21-192	22-205
Height (h) in metres	1,20-5,0	1,50-5,5	1,35-5,94
Pillar width (w) in metres	2,70-21,0	3,40-16,0	3,50-17,0
Extraction ratio (e)	0,37-0,89	0,45-0,91	0,44-0,88
Width to height ratio (w/h)	1,2-8,8	0,90-3,6	1,30-3,70

The frequency of occurrence of collapsed cases according to depth, pillar width, areal percentage extraction and ratio of pillar width to mining height is plotted in Figures 3.1 to 3.4.

Figure 3.1 plots depth versus frequency and shows that two-thirds of the collapsed cases occurred at a depth of less than 70 m with 34 per cent occurring below 40 m. Three 1966 to 1988 cases, Nos 148, 164 and 165, with safety factors of 1,52; 1,80 and 2,10 respectively, occurred at depths of 28,5 m, 33,0 m and 22,0 m.

Figure 3.2 plots frequency versus pillar width. Forty-three per cent of collapsed cases had pillar widths of less than 6,0 m while 29 per cent of the 1966 to 1988 collapses and 20 per cent of all collapses had a pillar width of less than 4,0 m. Cases Nos 165 and 148 had pillar widths of 3,5 m and 3,8 m respectively.

The areal percentage extraction versus frequency is shown in Figure 3.3. Two-thirds of the collapsed cases had an areal percentage extraction in excess of 75 per cent.

Figure 3.4 plots the pillar width to mining height ratio. Sixty per cent of all pillar collapses had a pillar width to mining height ratio less than 2,0, and it is significant that no pillar collapse has been recorded with a width to height ratio in excess of 4,0. Pillar collapse Cases Nos 115 and 157 had the highest width to height ratios of 3,58 and 3,74 respectively.

Safety factor versus frequency is plotted in Figure 3.5. As stated earlier, three 1966 to 1988 collapse cases, Nos 148, 164 and 165, had safety factors greater than 1,48 which was the highest safety factor of the pillar collapses used in the analysis by Salamon and Munro.

The number of pillars involved in all collapses between 1904-1988 versus frequency is plotted in Figure 3.6. Wherever possible the actual number of pillars has been obtained from the mine plans. These include most of the 1966 to 1988 pillar collapses. The remainder have been estimated as the mine plans no longer exist in the case of defunct collieries.

The time between mining and pillar collapse versus safety factor is plotted in Figure 3.7. Again the accuracy of this information in some cases can be questioned as very few dates were given on some of the mine plans. A considerable spread occurs in the time taken for pillar collapse to occur. Of the 38 cases where the time period is known, 26 per cent occur within the first year and 50 per cent within four years after mining. This figure includes cases where an extension to the original collapse occurred, and the time period was taken from the date of mining to the date of the extension of the pillar collapse. This was done to conform to the method used by Salamon and Wilson (1965).

3.4 DISCUSSION

It can be seen from the frequency diagrams that the 17 1966-1988 pillar collapses conform to the trend shown by the 27 pillar collapses recorded by Salamon and Munro in 1967. The 1966-1988 collapsed pillar cases reaffirm the results of Salamon and Munro's data rather than showing a new trend. However, there are two significant features in the analysis of the collapsed pillar cases.

Firstly, pillars at shallow depths of less than 40,0 m and with small pillar widths of less than 5,0 m, with a high percentage extraction in excess of 75 per cent and a width to height less than 2,0, are prone to pillar collapse, even with a designed safety factor in excess of the 1,6 which is recommended for the design of production panels. It is significant that the three cases, Nos 148, 164 and 165, fulfil one or more of the above criteria while, at the same time having a designed safety factor in excess of 1,48, which was the highest safety factor of all the pillar collapses analyzed by

Salamon and Munro. The parameters of small pillar width, shallow depth, high percentage extraction and low width to height ratio are interrelated and caution should be used when designing pillars at shallow depths.

An explanation for the pillars in this range being prone to collapse may be that the effects of blast damage, geological discontinuities, weathering and weak layers within the pillar influence the strength of small pillars more dramatically than they do the larger pillars. Salamon and Oravecz (1976) recognized the dramatic effect of a small reduction in pillar width when the pillar is less than 4,5 m in width; they suggested that no pillar be mined with a pillar width of less than 3,0 m and that pillars between 3,0 and 4,5 m in width should have a safety factor of at least 1,7.

This recommendation is insufficient to ensure stable pillar geometries and it is advisable, at depths less than 40,0 m, to select a minimum pillar width of say 5,0 m and maintain a width to height ratio in excess of 2,0; it is also recommended that the areal percentage extraction is no more than 75 per cent and that the safety factor is in excess of 1,6. In this way the stability of pillars at shallow depths will be greatly increased.

Secondly, it is highly significant that no pillar collapse has been recorded for width to height ratios greater than 3,74. This suggests that the pillar strength formula, although valid within its empirical range, underestimates the strength of a pillar as its width to height ratio increases, as suggested by Salamon and Oravecz (1976).

3.5 CONCLUSIONS

An analysis of the pillar collapses that have occurred during the period 1966 to 1988 do not show new trends but conform to the results given by the pillar collapses between 1904 to 1965. This confirms that the pillar strength formula of Salamon and Munro (1967) is very successful in designing stable bord and pillar geometries within the empirical range used to develop the formula. No pillars, designed to Salamon and Munro's pillar strength formula, have collapsed during their formation. Where collapses have occurred, some time after mining, either the safety factor was below the recommended 1,6 or small pillars were mined at shallow depth of less than 40,0 m.

At these shallow depths designing to a safety factor alone will not ensure pillar stability. It is therefore recommended that pillars mined at shallow depths have a minimum pillar width of 5,0 m, a width to height ratio in excess of 2,0, an areal percentage extraction not exceeding 75 per cent and a safety factor in excess of 1,6.

While stable bord and pillar workings can be ensured using Salamon and Munro's design method, the fact that no pillar has collapsed with a width to height ratio greater than 3,74 suggests that the strength formula underestimates pillar strength as the pillar's width to height ratio increases.

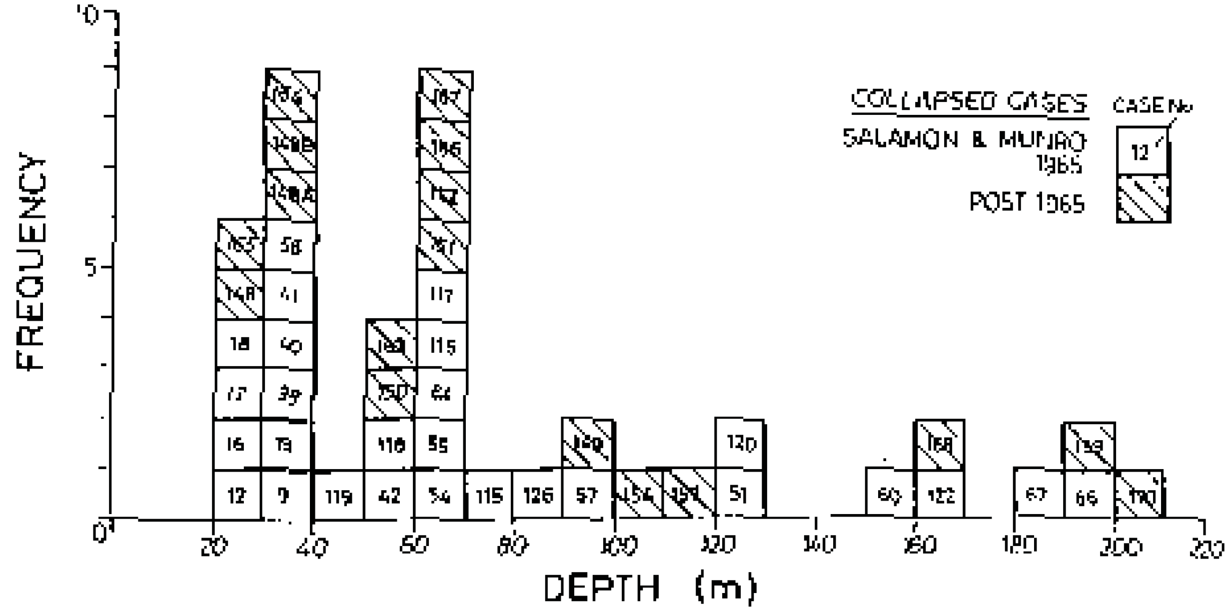

Figure 3.1 Frequency of occurrence versus depth of collapsed pillar cases.

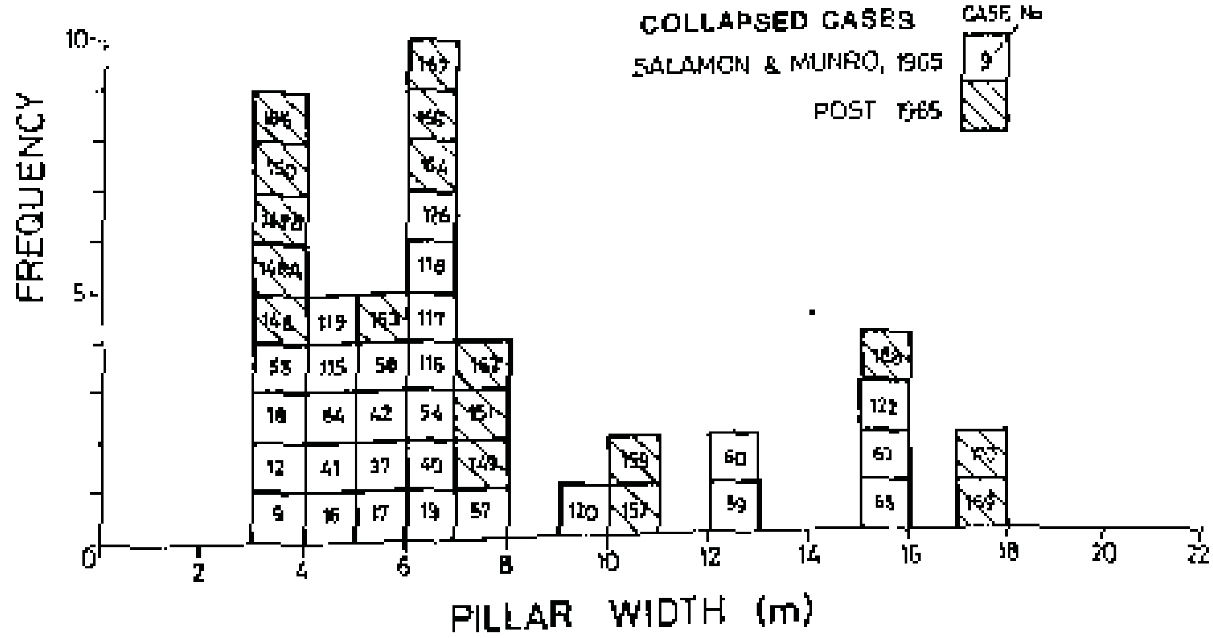

Figure 3.2 Frequency of occurrence versus pillar width of collapsed pillar cases.

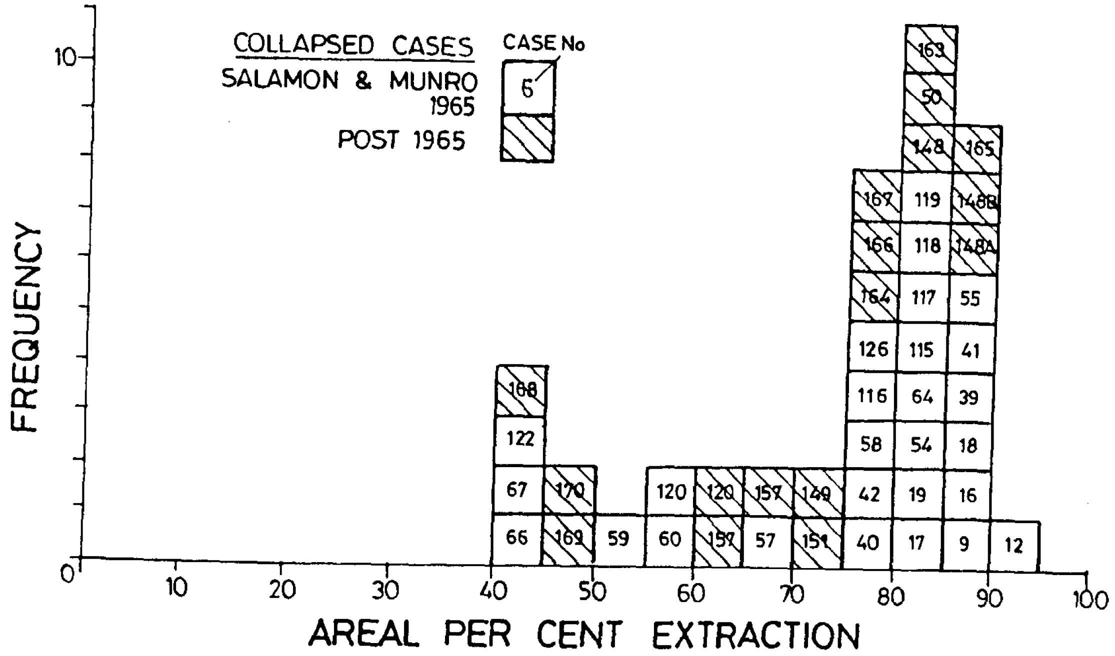

Figure 3.3 Frequency of occurrence versus the areal percentage extraction of collapsed pillar cases.

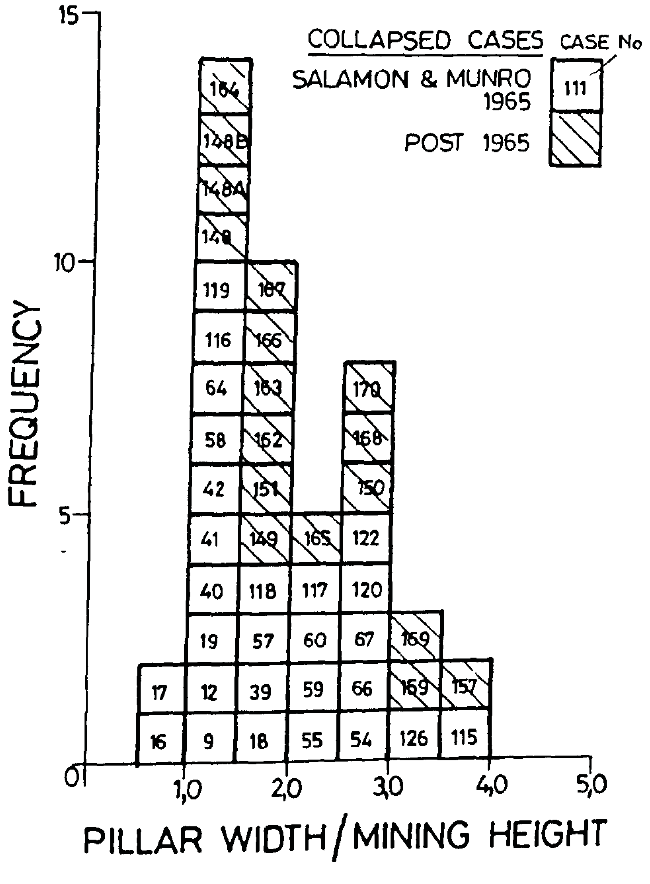

Figure 3.4 Frequency of occurrence versus the pillar width to mining height ratio collapsed pillar cases.

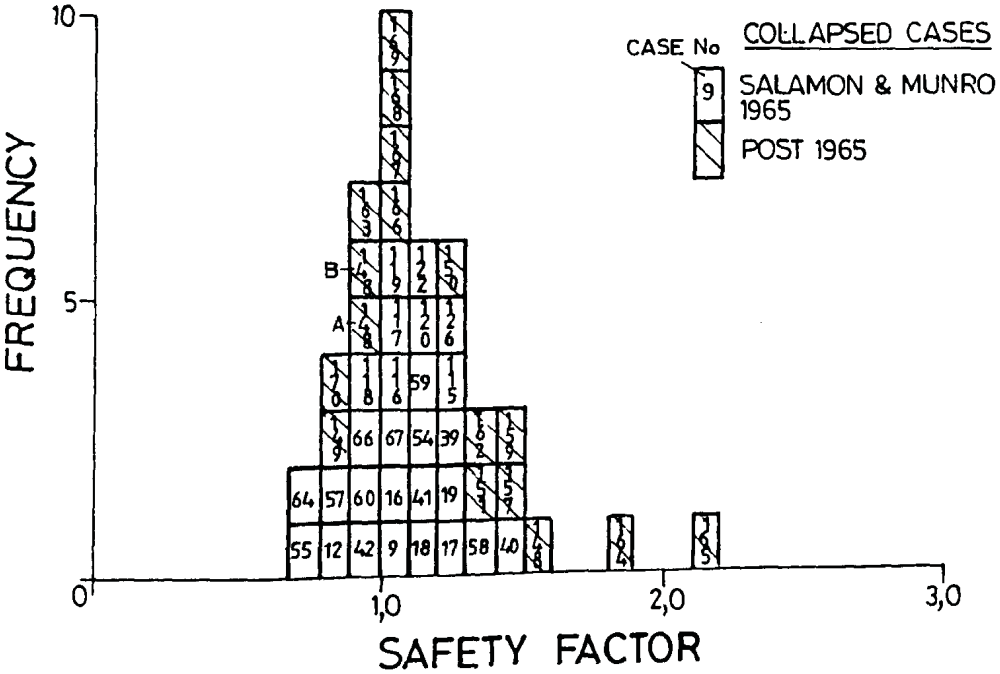

Figure 3.5 Frequency of occurrence versus the designed safety factor for collapsed pillar cases.

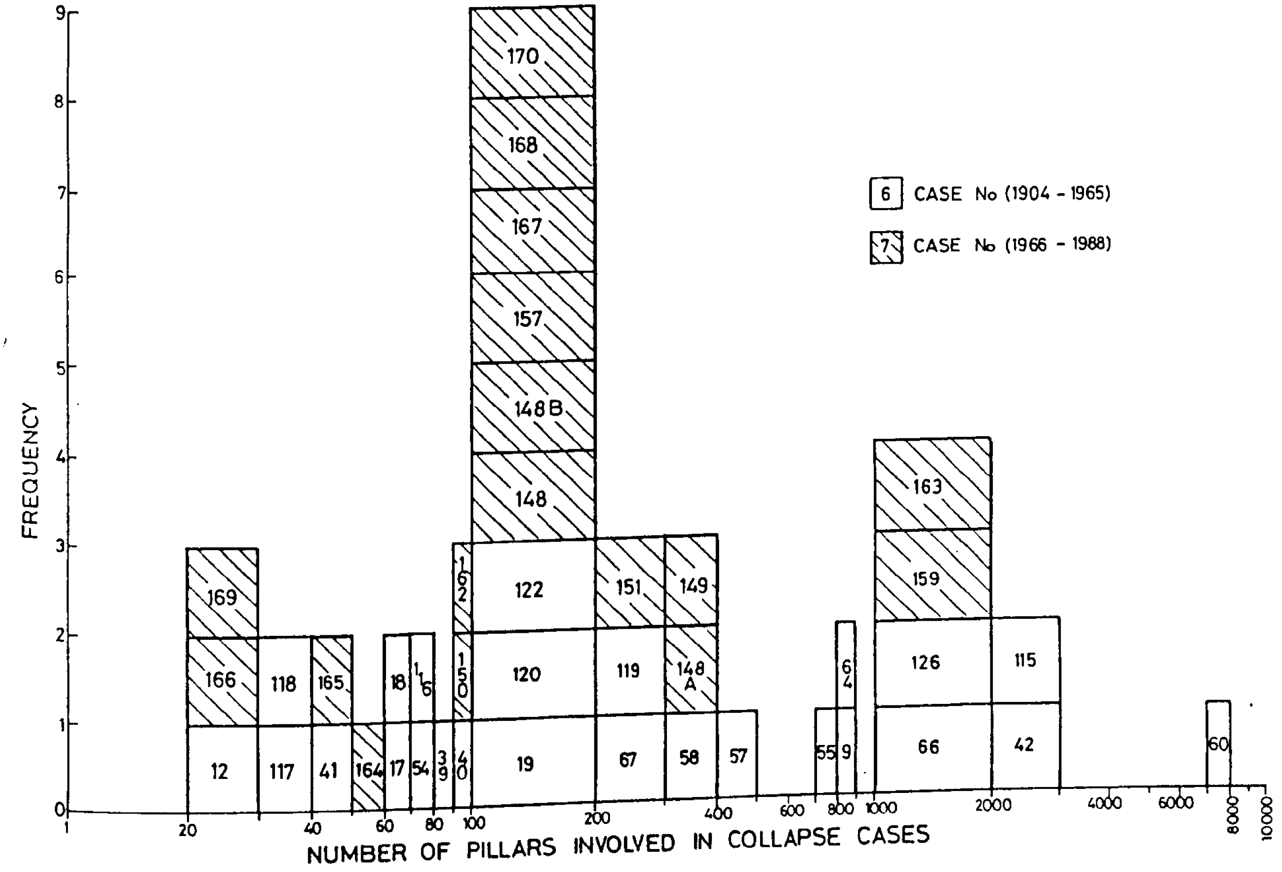

Figure 3.6 Frequency of occurrence versus the estimated number of pillar collapses.

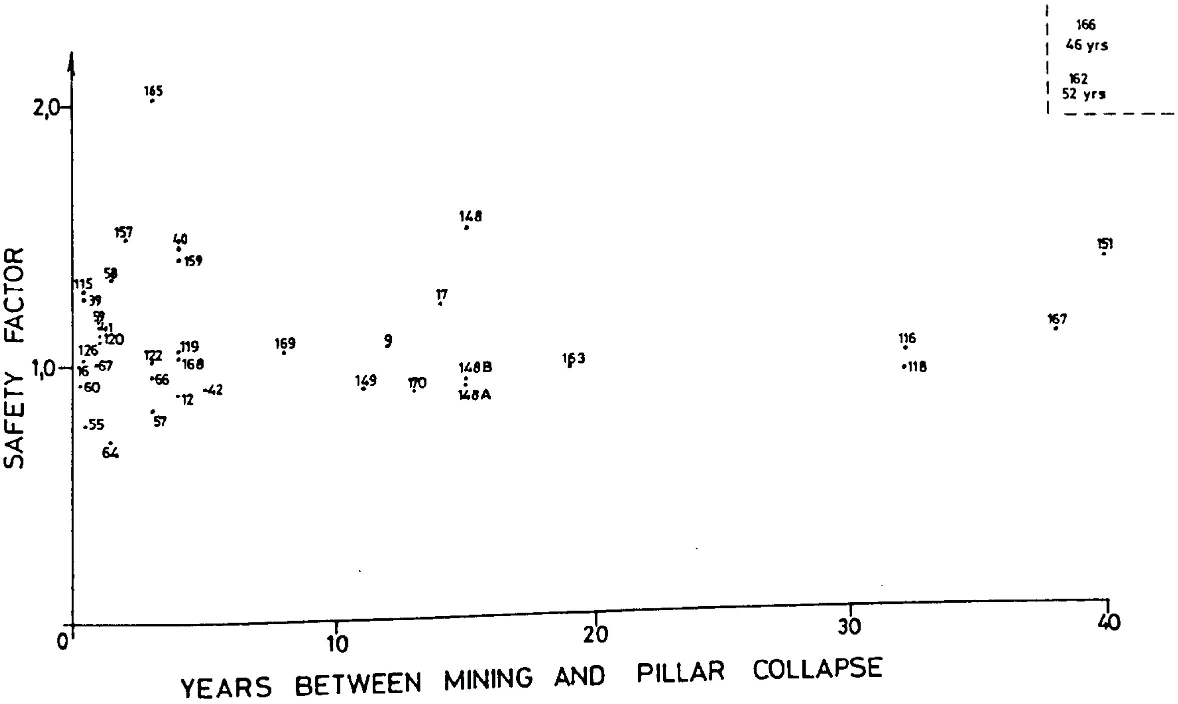

Figure 3.7 Safety factor versus the time period between the mining and collapse of coal pillars.

CHAPTER 4

INDIVIDUAL SEAM STRENGTH

4.1 INTRODUCTION

To examine the problem of determining individual seam strength two approaches were adopted. Firstly, as the statistical method of Salamon and Munro proved successful in determining the pillar strength formula, giving an average strength for all coal seams, the same method is used to determine individual seam strength. Secondly, the performance of an estimated two million coal pillars formed using Salamon and Munro's strength formula was examined using a classification system developed with the aim of quantifying individual seam strength.

4.2 STATISTICAL ANALYSIS

4.2.1 Statistical Model

The statistical method using the maximum likelihood function to calculate the values of k, α and β in equation 2.2 was available from the Department of Statistics, University of the Witwatersrand, through a computer program known as SAS.

The dimensions of all 27 collapsed cases were back calculated as were 92 of the 98 intact cases. The estimated values of k, α and β using these dimensions were compared to those quoted by Salamon and Munro (1967), Table 4.1, and the results showed that there was a close similarity between the parameters of k, α and β, including the 95 per cent confidence limits.

Table 4.1 Estimates of k, α and β For 27 Collapsed and 92 Stable Cases.

Parameters	k	(95% confidence limits)	
		α	β
All cases Salamon and Munro(1967)	7,176	-0,6609(-0,50 -0,82)	0,4590(0,32 -0,60)
27 Collapsed and 92 intact	6,910	-0,65 (-0,52 - 0,86)	0,45 (0,34 -0,64)

The dimensions of the 17 collapsed pillars which occurred between 1966 and 1968 were added to the original 27 cases to examine the influence on the strength formula of Salamon and Munro by inclusion of these pillar collapses. The values obtained for k, α and β are shown in Table 4.2 and the plots of strength versus load are shown in Figure 4.1.

The results show an increase in both α and β with a corresponding increase in the range of the 95 per cent confidence limits, where the parameter k is reduced from 7,176 to 5,240. Plots of strength value versus pillar width to height ratio using the pillar collapse cases between 1904 and 1966 and those between 1904 and 1988 for a mining height of 2,0 m are given in Figure 4.2. The strength calculations show very little difference over the range of width to height ratios 2,5 to 6,0 , although a required higher strength is calculated from the collapsed cases between 1904 and 1988 for pillar width to height ratios less than about 2,0. This accounts for pillar collapses with low width to height ratios at very shallow depth. However, the additional 17 collapsed pillar cases that have occurred between 1966 and 1988 confirm that the design method of Salamon and Munro remains valid. The differences in percentage extraction, for a safety factor of 1,6 over depths of 50 to 200 m with a 2,0 m mining height, are also minimal : 1,77 per cent difference at 50 m and 1,29 per cent difference at 200 m.

Table 4.2 shows the confidence intervals for the 1904-1988 pillar cases to be very wide and that the absolute correlations between parameter estimates are high.

As the 95 per cent confidence limits were increased by adding the 1966-1988 collapsed cases, it was decided to examine the effect of fixing α, then β and finally α and β in an attempt to reduce the 95 per cent confidence limit. The results are shown in Tables 4.3 to 4.5.

The range of the 95 per cent confidence limit for k reduces only in the case where α and β are both fixed. It was thus concluded that when using the statistical method on individual seams the parameters α and β should be fixed.

Table 4.2 Pillar Strength Parameters From the Maximum Likelihood Function.

Data	Salamon and Munro (1967)	Collapsed cases 1904-1988
Collapsed pillars	27	44
Intact pillars	98	92
Total pillars	125	137
Parameter estimates 95 per cent confidence limits		
k	7,176	5,240
α	-0,66(-0,50 to -0,82)	-0,78 (-0,52 to -0,99)
β	0,46 (0,32 to 0,60)	(0,63 (0,39 to 0,87)
Correlation Coefficient		
Log(k) with α	-0,23	0,38
Log(k) with β	-0,65	-0,85
α and β	-0,57	-0,75

Table 4.3 Pillar Strength with β Fixed.

Data	Salamon and Munro (1967)	Collapsed cases 1904-1988
Fixed β	0,46	0,46
Parameter estimates and 95 per cent confidence limits		
k	7,21 (6,00 ; 8,66)	7,14 (5,79 ; 8,81)
α	-0,67 (0,30 ; 0,64)	-0,71 (-0,87 ; -0,55)
Correlation Coefficient		
Log(k) with α	-0,95	-0,95

Table 4.4 **Pillar Strength with α Fixed.**

Data	Salamon and Munro (1967)	Collapsed cases 1904-1988
Fixed α	0,66	-0,66
Parameter estimates & 95 per cent confidence limits		
k β	6,81 (5,39 ; 8,60) 0,47 (0,30 ; 0,64)	6,99 (5,43 ; 9,10) 0,44 (0,31 ; 0,57)
Correlation Coefficient		
Log(k) with β	-0,97	-0,97

Table 4.5 **Pillar Strength with α and β Fixed.**

Data	Salamon and Munro (1967)	Collapsed cases 1904-1988
Fixed α Fixed β	-0,66 0,46	-0,66 0,46
Parameter estimates and 95 per cent confidence limits		
k	6,88 (6,50 ; 7,29)	-6,78 (6,34 ; 7,24)

4.2.2 Estimate of Individual Seam Strength

The assumption of one average strength for all seams in the pillar strength formula was stated by Salamon and Munro (1967) to be one of the causes for the scatter of failed cases around the safety factor of 1,0. However, they noted, the distribution of collapsed cases is quite narrow and only a very efficient technique of estimating the local value of k is likely to concentrate the distribution appreciably.

Given that 17 additional collapsed cases have occurred since the original analysis, there is now more information on collapsed cases in individual seams, particularly the No. 2 Seam of the Witbank Coalfield where 15 collapsed cases have been recorded.

To obtain an estimate of individual seam strengths, the analysis was conducted using collapsed and intact cases from the individual seams. The results of the Nos 2, 4 and 5 Seams from the Witbank Coalfield are shown in Table 4.6.

Table 4.6 Pillar Strength Estimate for Individual Seams Fixing $\alpha = -0{,}66$ and $\beta = 0{,}46$.

Seam	No. of Collapses	No. of Intact Cases	Strength Estimate	95% Confidence Limit
W2	15	43	6,92	(6,23-7,70)
W4	8	8	7,65	(6,98-8,38)
W5	5	7	5,88	(4,62-7,65)

The confidence limits for k in Table 4.6 are very wide and overlap for the three seams. These results indicate that there is no statistically significant difference in mean strength between the seams that can be detected by this method.

The limited data in all seams, except for the No. 2 Seam of the Witbank Coalfield, may be another reason for the scatter of results. It is encouraging that the scatter of the mean values is fairly small around the average strength of the seams shown in the table. Other seams, as a result of their limited number of either collapsed or intact cases, gave meaningless results.

However, the maximum likelihood function is the best method for fitting a model to this type of data. The reasons for the scatter of results may be a result of the same factors stated by Salamon and Munro (1967), that is human error in calculating incorrect dimensions and irregularities in mining layout, the approximate nature of the strength formula, and natural variations in coal strength, seam structure and the quality and influence of roof and floor conditions.

4.2.3 Conclusions From The Statistical Analysis

Adding the pillar collapsed cases occurring between 1966-1988 to the original cases used by Salamon and Munro and using the same statistical method resulted in a change in values for the parameters k, α and β. The strength values, using the new parameters, showed that little variation in strength (maximum 10 per cent) occurred between the values of width to height ratios 2,0 to 6,0 compared to those originally calculated by Salamon and Munro. At lower width to height ratios the increased strength required obtained using the 1904-1988 collapsed cases reflects the fact that low width to height ratio pillars are prone to collapse which confirms the results obtained in Chapter 3.

The maximum likelihood function suggested minimal variation in the estimation of individual coal seam strength; however, the results were inconclusive in all seams due to the limited data.

4.3 ASSESSMENT OF COAL SEAM STRENGTH ON THE BASIS OF VISUAL EXAMINATION OF BORD AND PILLAR WORKINGS

Because of the lack of a sufficiently large number of failed bord and pillar workings in the various coal seams, and also the difficulties of determining the strength of individual seams by means of large-scale testing, a visual method of assessing seam strength was developed based on the performance of coal pillars since their formation. Details of the method and the results obtained are presented in this section.

4.3.1 Rationale of Classification System

From laboratory experiments on quartzite specimens by Hallbauer et. al. (1973) and large-scale coal pillar tests by Wagner (1974), it is known that in a compressive stress environment the first signs of rock fracturing are observed well before actual structural failure. In the case of a confined cylindrical rock specimen, Hallbauer et. al. (1973) found a significant increase in microfracturing at a stress level of about 0,8 times the stress at failure. Wagner (1974) observed that in the case of square coal pillars the corners of the pillar and the unconfined pillar sides fractured well before the failure load was reached. An important observation made by Wagner (1974) was that the stress level at which the unconfined corners of the various test pillars failed was virtually constant and was independent of the width to height ratio of the pillar, whist the ultimate strength of the pillars increased when the width to height ratio increased. Careful observation of the extent and severity of fracturing of pillar corners and sides can therefore provide a useful indication of the unconfined strength of coal.

A prerequisite for the visual assessment of coal seam strength is that the stresses acting on the corner and side of a coal pillar should approximate the same order of magnitude of the unconfined strength of the seam. If the stress levels are well below the strength of the seam, few if any fractures will be observed. However, in the case of very high stress values, the extent of fracturing will be so severe that no conclusion other than that the unconfined strength has been exceeded can be reached.

In order to assess the suitability of the visual assessment method for the strength evaluation of coal seams, skin and average pillar stress values have been calculated. The stress values at the pillar's skin or edge were obtained using the computer program MINAP. Although MINAP is a two-dimensional program modelling infinite strips of pillars, the three-dimensional pillar stresses were obtained by reducing the elastic modulus of the pillars by the method described by Ozbay (1987). In this method the two-dimensional modulus is obtained by the product of the three-dimensional modulus of the pillar and the extraction ratio along the length of the strip pillar. Thus the strip pillar's stiffness is reduced resulting in the same average convergence as that as the row of square or rectangular pillars. The average induced stresses acting on the pillars were then calculated by dividing the stress obtained across an element by the extraction ratio along the length of the strip pillar.

The results are shown in Figure 4.3, for seam depths ranging from 30 to 150 m and pillars designed to safety factors of 1,5 and 2,0. Also shown in Figure 4.3 are the strength value, k, of a cube of coal 1,0 m in length which, according to Salamon's pillar strength formula, is 7,2 MPa, with upper, k_u, and lower, k_l, strength boundaries given by $k_u = k + 0{,}25\ k$ and $k_l = k - 0{,}25\ k$.

An examination of the strength and stress values in Figure 4.3 indicated that meaningful results from the visual method can be expected over the depth range 50 to 120 m. At depths less than 50 m the stresses are generally too low to cause significant fracturing of pillar corners and sides, whilst at depths of greater than 120 m the theoretical stress values are far in excess of the unconfined strength of even the strongest coal seams, $k + k_u$, and excessive fracturing is likely to be observed.

Figure 4.4 shows the average depth and stress values for seven different coal seams covered by this investigation. For convenience of reporting the seams have been labelled I to VII, where

Seam I	is the No. 2 Seam Witbank Coalfield
Seam II	is the No. 4 Seam Witbank Coalfield,
Seam III	is the No. 5 Seam Witbank Coalfield,
Seam IV	is the No. 3 Seam Orange Free State Coalfield,
Seam V	is the Lower C Seam Ermelo-Bryeton Coalfield,
Seam VI	is the Upper C Seam Ermelo-Bryeton Coalfield,
Seam VII	is the B Seam Ermelo-Bryeton Coalfield.

In terms of the strength and stress criteria, Seam Nos III, VI and VII fall outside of the ideal area of application of the visual method of estimating pillar strength, and are unlikely to show significant amounts of fracturing except where the coal seams are very weak.

Ideally, the visual method of seam strength evaluation would require that the pillar stresses cover a wide range so as to accurately relate the extent of fracturing to stress levels. Unfortunately, with the exception of Seam I, the variation in stress levels in individual seams was rather small. For this reason Seam I has been used as the reference.

Finally, the evaluation of the coal seam strength characteristics has been based on average pillar stress values rather than on skin stresses. The latter are difficult to determine in specific instances as they depend on local pillar geometry, the properties of the seam and roof and floor strata, and the contact of the seam with the surrounding strata. According to Figure 4.3, in the depth range 50 to 100 m the skin stress is $\sigma_{sk} \simeq k \pm 0{,}25\ k$.

4.3.2 Pillar Rating System

Pillar condition is rated in two stages. Firstly, the condition of the pillar is described and recorded on a special form. This step is called the classification process. Secondly, each observation is rated according to the relative importance of the parameter. This step is called the rating process.

(A) Classification Process

The pillar classification process is based on detailed visual observations of pillar conditions. After a bord and pillar panel is visited and the overall ground and pillar conditions in the panel observed, a specific pillar near the centre of the panel is selected for detailed classification. The pillar and bord dimensions are measured and the condition of the pillar corners and sides, as well as details of cracks and weaknesses in the pillar, are entered on a special form (Table 4.7). An example of the classification and rating processes for a specific case is shown in Tables 4.7, 4.8 and 4.9.

Stone dusting, which is required by law to safeguard against the possibility of coal dust explosions, was found to be a useful indicator of a deterioration in pillar condition over time and of the amount of spalling that has taken place. Therefore, in addition to the amount of stone dust remaining on the pillar, the time of application of stone dusting is noted.

Bands of other geological material within the coal seam are recorded as they can influence the strength of the pillar. Similarly, details of the contact of the pillar with the roof and floor are carefully noted.

For the sake of completeness and future reference, roof conditions in the bord and pillar workings are recorded, as well as details of roof falls. Roof failures are known to be a cause of pillar failure since they increase the effective height of pillars and thereby reduce the strength of the pillars. A record is also kept of the roof support details such as type, density and pattern.

Faults, slips and joints may likewise influence the strength of the roof or pillar. For this reason the orientation, spacing and persistence of these geological discontinuities are determined. From this information regional and local densities of discontinuities can be determined and taken into account in the analysis of the strength properties of coal seams. Finally, details of the depth of mining, design dimensions, date and method of mining and composition of the superincumbent strata are obtained from the survey department of the mine (Table 4.8).

(B) Rating Process

The purpose of the rating process is to arrive at a quantitative assessment of the pillar conditions in a particular coal seam with the main emphasis o the parameters which affect the strength of a pillar.

The parameters recorded during the pillar classification process were grouped into three categories depending on their importance with respect to the assessment of coal seam strength. Within each category five grades were introduced to allow for the differences in conditions recorded in Table 4.7.

The first category concerns the most important parameters, namely:

(i) spalling of the pillar sides and corners, expressed as a percentage of the mining height,

(ii) discontinuities, and

(ii) punching of pillar into the roof and floor.

Rating in the first category is done at intervals of 25 from 0 to 100 points. A low rating indicates poor conditions while a high rating refers to good or excellent conditions

The second category comprises parameters which are considered of secondary importance for the assessment of coal seam strength, namely:

(i) weaknesses in the pillar, and

(ii) deterioration due to weathering and changes in ventilation.

Rating in the second category is from 0 to 20 at intervals of five. The third category refers to observations which are indicative of pillar performance, for example stone dusting. As in the case of the second category, rating is from 0 to 20, but there are 25 grades. In this category the amount of visible stone dusting is weighted by the time at which stone dusting was applied. (Table 4.9).

Finally, the length of time that bord and pillar workings has been standing is also an important factor in the assessment of seam strength properties since it is well known that the strength of rock is time dependent. Since coal pillars are designed for a long life, it is obvious that observations of pillar conditions in old workings are of greater significance than those observed in recently mined areas. For this reason the pillar condition, R_c, obtained in Table 4.9 is weighted by the time factor, T_F, whereby the final rating, R_T, is given by

$$R_t = R_s T_f \qquad (4.1)$$

The time factor T_F is given by the following relationship

$$T_f = \ln 3{,}304 t^{0{,}08} \qquad (4.2)$$

where t is the age of the pillar in years and 3,304 and 0,08 are arbitrarily chosen constants, based on the fact that the longer a pillar has remained intact the higher the time factor given.