AN INVESTIGATION INTO THE FACTORS AFFECTING THE STRENGTH OF PILLARS IN SOUTH AFRICAN COAL MINES

Bernard John Madden

A thesis submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg 1990

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Madden

Bernard John Madden

Dated this 7th day of September 1990

ABSTRACT

Salamon and Munro's back analysis of collapsed and intact pillar geometries resulted in a pillar design formula that has been used exclusively in South Africa for the past 22 years. During this period the exploitation of coal seams has increased considerably.

This thesis presents investigations into Salamon and Munro's pillar strength formula which were conducted with the aim of examining the formula's application to current mining practice as well as identifying modifications that will lead to increased productivity and extraction.

It is shown that the application of Salamon and Munro's pillar strength formula results in stable pillar geometries within the empirical range used to develop the formula. However, at depths shallower than 40 m it was found designing to a safety factor alone was not sufficient; a recommended minimum pillar width and pillar width to mining height ratio and a maximum areal percentage extraction should be adhered too for long term stability.

The assumption of an average seam strength in Salamon and Munro's strength formula was investigated, firstly by the same statistical method used by Salamon and Munro and secondly, by a classification system designed to rate pillar performance. Although a qualitative difference in individual seam strength is detected by both methods, the results show considerable overlap suggesting that assuming one average strength for all coal seams is reasonable.

The effect of blast damage on pillars, as a result of the conventional drilling and blasting mining method, is quantified. As a continuous miner formed pillar does not have a blast damage zone, the pillar width can be reduced resulting in an increased extraction.

Field evidence suggests that Salamon and Munro's formula underestimates pillar strength for pillars with high width to height ratios. To examine the influence of geometry on strength, an extensive laboratory testing programme was undertaken. The results showed a significant strength increase after a certain width to height ratio. An extension of Salamon and Munro's formula by Salamon (1982), termed the "squat" pillar formula, fits the strength increase of the high width to height laboratory specimens well.

Results of field experiments conducted on pillars designed to the squat pillar formula validate the formula as a realistic extension of Salamon and Munro's strength formula for pillars with large width to height ratios.

As a result of this investigation, the South African coal mining industry is designing stable pillar geometries that account for depths shallower than 40 m, the effect of mining method on pillar strength and the influence of geometry on the strength of high width to height pillars. This has resulted in increased productivity and extraction of reserves without jeopardizing the safety of the underground workings.

ACKNOWLEDGEMENTS

I wish to express my gratitude to :

Professor S. Budavari, University of the Witwatersrand, for being the thesis supervisor and giving invaluable advice during the progress of the thesis.

Dr. H. Wagner, Senior General Manager Operations, Chamber of Mines of South Africa, for supporting this project and his guidance, constructive criticism and encouragement as well as acting as COMRO's thesis supervisor.

Mr. D. Hardman, Director, Coal Mining, Chamber of Mines Research Organization, for supporting the project through to its completion.

I would also like to acknowledge the contribution of the following :

- The Chamber of Mines Research Organization for sponsoring the research,
- The Strata Control Advisory Committee for their financial assistance,
- Mr. G. Prohaska who spent many days with me during the numerous underground field experiments.
- I have benefited from open discussion of my work from my COMRO colleagues in particular Andre Vervoort, Robin Hill, Bruce Jack and Turgay Ozan, also my numerous colleagues in other departments for their assistance during the preparation of the thesis.
- The colliery managers who assisted the research project by their cooperation, in particular Mr. D. Visage, Piet Retief Colliery and Mr. C. Edwards, Hlobane Colliery.
- Dr. R. Brummer, University of the Witwatersrand, for the use of his program SEAMS as well as reviewing Chapter 7.
- Mr. W. Van Heerden, Programme Manager, CSIR, for the loan of intrinsically safe equipment.

Lastly, but not least, I thank my wife, Antje, and children, Gisela, Patrick and Christine for their support, patience and sacrifice during the time taken to complete this project.

CHAPTER 2
LITERATURE SURVEY

CHAPTER 3
REVIEW OF THE PERFORMANCE OF COAL PILLARS DESIGNED USING SALAMON AND MUNRO'S STRENGTH FORMULA.

CHAPTER 4
INDIVIDUAL SEAM STRENGTH

CHAPTER 5
THE EFFECT OF MINING METHOD ON PILLAR STRENGTH

CHAPTER 6
SQUAT FORMULA LABORATORY TESTS

CHAPTER 7
INVESTIGATION INTO THE DESIGN OF SQUAT PILLARS

CHAPTER 8
CONCLUSIONS AND PROPOSED FURTHER STUDIES.

LIST OF FIGURES

Chapter 2 Page No.

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

APPENDIX I

LIST OF TABLES

Page.

Table

LIST OF SYMBOLS

A : area supported by pillars

A_p : area of pillar

A' : area of specimen

C : pillar centre distance

C' : cohesion

E : Young's modulus

H : mining depth

L : load on pillar

N : normal force

R : pillar width to height ratio

R_c : pillar condition

R_o : critical width to height ratio

R_T : pillar rating

S : safety factor

S_c : critical safety factor

SED : strain energy density

S' : shear force

T_f : time factor

V : pillar volume

a : constant

b : constant

e_a : areal extraction ratio

e_{cm} : areal extraction ratio for continuous miner

g : acceleration due to gravity

h : mining height

k : strength of unit cube of coal

m : constant

s : constant

t : age of pillar

w : pillar width

w_c : pillar width-continuous miner formed pillar

w_d : pillar width-drill & blast formed pillar

Δw_d : blast damage zone

α : constant

β : constant

γ : dimensionless parameter

δ : dimensionless parameter

ϵ : rate of strength increase

ϵ' : axial strain

η : constant

λ : measure of scatter

ρ : overburden strata density

ν : Poisson's ratio

σ_p : pillar strength

σ_c : strength of cubic specimen

σ_1 : major principal stress

σ_3 : minor principal stress

σ_n : normal stress

τ_{ns} : shear stress

ϕ : angle of friction

ψ : angle of fracture

CHAPTER 1

1.1 INTRODUCTION

Some 80 operating collieries currently produce approximately 180 million tons of coal annually in South Africa. Some 120 million tons is produced from underground operations with about 75 per cent of this figure from bord and pillar workings. Even in deeper collieries, where production is mainly by total extraction methods, bord and pillar mining is practised in those areas subject to surface restrictions (up to 30 per cent in some cases). Therefore the optimum design of pillars is critical for the safe, economic and productive extraction of reserves while at the same time maximizing a finite resource.

In bord and pillar mining, production panels must be designed to satisfy two contradicting requirements, that of being as small as possible to maximize extraction and productivity as well as being large enough to provide permanent long term support. Where pillar extraction is practised, the pillars must be of sufficient strength to enable extraction without being oversized which would result in reduced productivity of primary operations because of the excessive tramming distances.

In the deeper collieries, main developments are typically driven with five roadways for ventilation purposes. These roadways form pillars and, although these pillars may be extracted at the end of the life of the mine, large pillar sizes result in low productivity from development panels.

Significant research has been conducted in South Africa towards the development of a suitable pillar design method. A major advance in rock mechanics occurred with the statistical analysis of intact and collapsed coal pillars, Salamon and Munro (1967), which led to the development of a pillar strength formula based on full size pillars. This formula has been used exclusively in the design of coal pillars in South African collieries for the past 22 years.

During this period, the coal mining industry has expanded considerably. Numerous collieries now mine seams outside the empirical range of the design formula, and thus the extension of the design formula to these collieries requires examination.

For example, as mining operations reach greater depths, the width to height ratio tends to increase, and it has been suggested that at higher ratios this increase was more rapid.

In addition, over the past twelve years production from continuous mining machines has increased to the extent that 30 per cent of all coal from bord and pillar workings is mined using a continuous miner. As the design formula of Salamon and Munro (1967) was based on pillars formed by drilling and blasting methods, the effect of blast damage on a pillar is inherently included in their formula. The effect of the continuous mining method on pillar strength needs to be quantified, as, because of the absence of blast damage, the strength should be greater. Such a pillar could be mined to smaller dimensions than a pillar formed by drilling and blasting and maintain the equivalent strength. This would lead to increased extraction without decreasing the stability of the workings.

Pillars designed to the same nominal safety factor in different seams have been observed to perform differently. As the pillar strength formula of Salamon and Munro assumes one strength for all coal seams, the strength of individual seams requires investigation.

In this thesis the literature pertaining to coal strength is reviewed and the results obtained in South Africa discussed in Chapter 2. In Chapter 3 Salamon and Munro's pillar strength formula is re-evaluated in the light of additional information regarding pillar collapses. This additional information is analysed in Chapter 4 by the same statistical method used by Salamon and Munro (1967) with the aim of evaluating individual seam strengths. A classification system is presented to quantify pillar performance so that individual seam strengths can be identified.

The effect of mining method on seam strength is examined in Chapter 5. Although first suggested by Wagner (1980), there has been no investigation into quantifying the effects of blasting on pillar strength.

In Chapter 6 the effect of geometry on strength is examined. An extensive laboratory testing programme on the influence of width to height ratio on

results are used to examine the suitability of

Munro's strength formula, termed the "squat"

alamon (1982).

The results of monitoring and numerical modelling of coal pillars designed to the squat pillar formula are contained in Chapter 7. Benefits of applying the squat pillar formula, in terms of extraction and productivity, are discussed.

The objective of this thesis is to apply rock mechanics principles to the improved design of pillars by an examination of the factors that affect their strength, namely seam strength, mining method and pillar geometry.

The South African coal mining industry has applied the results of this thesis, resulting in improved productivity and increased percentage extraction without decreasing the safety of the underground workings. Notably, as a result of the work presented in this thesis, the South African Government Mining Engineer has formerly approved the extension of Salamon and Munro's strength formula by the squat pillar formula.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

Coal pillar design is of primary importance for the safe, economic extraction of a valuable national resource. Initially, pillar dimensions and road widths were based on experience obtained through trial and error. However, the errors committed have had disastrous consequences in terms of loss of life, equipment and coal reserves. Thus, research efforts worldwide have concentrated on the development of an effective design procedure that can be used by collieries.

This more rational approach to the determination of coal pillar strength began early this century with the testing of coal specimens in the laboratory. General trends were quickly established, such as a decrease in the specimen strength with increasing height and size and an increase in strength with increasing width. However, the wide scatter of results made the extrapolation of strength results to full size pillars extremely difficult. To overcome the limitations of laboratory tests, the testing of large in situ samples was then initiated. These experiments had the advantage of tests being conducted in the underground environment and yielded valuable information regarding the stress-strain behaviour of coal pillars. However, these tests were time consuming, expensive and did not overcome the problem of extrapolation of results to full size pillars.

2.2 SALAMON AND MUNRO'S DESIGN PROCEDURE

The extensive collapse of bord and pillar workings at Coalbrook Colliery in January 1960 resulted in the loss of 437 lives. This tragic disaster was detailed by Bryan et. al. (1964) together with the relevant geology, possible failure mechanisms and current knowledge of the strength of coal pillars. It was apparent that, despite the investigations conducted worldwide over many years into coal pillar strength, no confirmed method of calculating pillar strength existed. This resulted in an intensive investigation in South Africa into the strength of coal pillars and led to the study of the strength of coal pillars by the statistical analysis of 98 intact and 27 collapsed pillar geometries by Salamon and Munro (1967). These authors used a probabilistic notion of safety factor where this factor was defined as:

$$Safety\,factor = \frac{strength}{load} \qquad (2.1)$$

The values for strength and load must be regarded as predictions which are subject to error. Hence the critical safety factor (S_c) calculated from the predicted strength, and the load at failure, will be either smaller or greater than unity. The exact value of S_c is not known in practice and the stability of a structure is ensured by employing a safety factor with an acceptably high probability of ensuring a stable geometry, that is S>Sc.

Figure 2.1 shows that the collapsed cases cluster around a safety factor of 1,0 , where the chances of failure and stability are equal, whereas the intact cases are distributed over a wide range. Salamon (1967) thought it reasonable to suppose that the majority of mining engineers arrived at an acceptable compromise between safety and economic mining and that the optimum safety factor lay in the range where 50 per cent of the stable cases are most densely concentrated. This occurs between safety factors of 1,3 to 1,9 with the mean being 1,6. It is this value that was recommended for the design of production pillars in South African bord and pillar workings.

Load is calculated using the modified cover load or Tributary Area Theory, whereby each individual pillar is assumed to carry the weight of the overburden immediately above it. This assumption applies where the pillars are of uniform size and the panel width is larger than the depth to the seam. These conditions are fulfilled by the majority of bord and pillar panels in South African collieries.

Strength is taken to mean the strength of a coal pillar as opposed to the strength of the coal. The strength of a pillar was said to depend on the material strength as well as the pillar's volume and shape. The shape effect was said to be a result of constraint imposed on the pillar through friction or cohesion by the roof and floor.

The general formula for strength was given as:

$$\sigma_p = k h^{\alpha} w^{\beta} \tag{2.2}$$

In this equation σ_p is the pillar strength, k is the strength of a unit cube of coal, α and β are appropriately chosen constants, w is the pillar width and h is the pillar height.

Estimates of the unknown constants k, α and β which would concentrate the distribution of critical safety factors about S = 1 were obtained using the maximum likelihood function. The symbol k does not represent the actual strength of a specimen but that of a pillar of cubic dimensions, and one average value was calculated in the analysis to represent the strength of all seams.

The result gave k as 7 176 kPa, α as -0,66 and β as 0,46. Figure 2.2 shows the intact and collapsed cases using these values. The scatter of results was said by Salamon to be due to three major causes:

(i) natural causes - that is, variations in coal strength, seam structure and the quality of the roof and floor;

(ii) the approximate nature of the strength formula; and

(iii) human error.

To examine the "size and shape" effects, the strength formula was re-written in terms of volume, $V = h.w^2$,and pillar width to height ratio, $R = w/h$, as

$$\sigma_p = k V^{a} R^{b} \tag{2.3}$$

where $a = -0{,}0667$ and $b = 0{,}5933$

The value of "a" suggests that the effect of size diminishes above a critical volume.

The design method is a considerable advance in the determination of the strength of coal pillars as it is based on full size pillars and overcomes the problems of extrapolating results from small laboratory or medium size in situ tests. However, there are a number of limitations in its application today and these require investigation. In particular, Salamon (1967) emphasized that the pillar strength formula was essentially empirical and should not be extended beyond the range of data used to derive it; currently, this is not the case in several collieries where both the depth of mining and the pillar width to height ratio exceed the empirical range.

Salamon and Oravecz (1976) considered the strength formula to be conservative when the width to height exceeds five or six and that a pillar with a width to height of 10 would be virtually indestructible.

Furthermore, the assumption in the formula of one average strength for all coal seams was recognized as a possible limitation by Salamon (1967).

Wagner and Madden (1984) also noted that coal pillars mined in different seams behaved differently despite being designed to the same safety factor. Some seams show no deterioration after mining while others display considerable signs of load.

The remainder of the literature survey is structured in two parts. Firstly, the question of coal strength is investigated with the aim of reviewing methods of obtaining individual seam strengths. Secondly, the validity of applying Salamon and Munro's strength formula to pillars as they become squatter is examined.

2.3 COAL STRENGTH

2.3.1 Laboratory Tests

The strength of rock has been examined for more than 100 years, with coal, being an important economic mineral, receiving particular attention. Early this century, several researchers in the USA and UK conducted laboratory tests on the strength of coal specimens. In particular, tests were conducted by Carpenter (1901) and Daniels and Moore (1907) with the purpose of designing bord and pillar workings. The results were reported and discussed by Bunting (1911) who stated that, under compression, anthracite fractures at various angles to the direction of applied force. This angle, it was stated, depends upon the brittleness of coal, its shearing strength and frictional resistance, all of which vary widely with different coals. Thus, the scatter of results was attributed to variations between coals, in addition to specimen preparation, discontinuities within the specimen and the individual material composition of each coal specimen.

Despite the crude preparation and testing methods and the wide scatter of results, these early laboratory investigations showed that, as the size of the specimen increases, the strength decreases, and, for the same specimen width, an increase in height resulted in a decrease in strength.

The strength of South African coal seams was first discussed by Steart in 1954. The strength of a one foot cube is quoted as varying from 15 to 170 tons, and four test results on nine inch square specimens of varying height from four to 27 inches taken from Durban Navigation Colliery are given. Steart states that the seams in the Ermelo and Breyton districts are very hard but no figures or test results are given to substantiate this statement. The strength of a square pillar is said to be greater than the strength of rectangular pillars having the same height and width in one direction. The influence of sandstone or hard shale layers within a coal pillar was discussed and said to reinforce the strength of a pillar considerably, although no evidence is given.

Steart also considered differences in hardness of samples or irregularities between specimens to be the reason for the wide scatter of laboratory strength results. In addition, he regarded laboratory test results as applying to the shape and size of specimens and not a direct indication of the strength of a full size pillar.

Between 1963 and 1969 considerable effort was made to determine the strength of coal from the Witbank coalfield and the investigations are summarized in Table 2.1.

TABLE 2.1 Summary of the Results of South African Laboratory Tests.

Reference	Colliery	Seam	Number of tests	Cube Size	Results
Steart(1954)	DNC			1 ft	15-170 ton - load carried at failure
Wiid(1963)	Witbank	No 1	29	1 in	Figure 2.3
Wiid(1963)	Witbank	No 2	71	1 in	Figure 2.3
Wiid(1963)	Witbank	No 4	23	1 in	Figure 2.3
CSIR(1965)	Wolvekrans	No 2	Uni & Triaxial	1.6 in	Figure 2.5
Bieniawski(1967b)	Witbank	No 2	4	1 ft	Table 2.2
Bieniawski(1968d)	Witbank	No 2	52	0,75 to 8 in	Table 2.3
Bieniawski(1967b)	Varied	Varied	579	1 in	
Kruger(1968)	Witbank	No 4	40	2 in	Figure 2.7
Kruger(1968)	Witbank	No 2	200	2 in	Figure 2.7
Merten(1969)	New Largo	No 4	6	1 ft	

Coal strengths and material properties for Seam Nos 1, 2 and 4 from the Wolvekrans Section of the Witbank Colliery in the Witbank Coalfield were recorded by Wiid (1963). Twenty-nine samples of No. 1 Seam, 71 samples of No. 2 Seam and 23 samples of No. 4 Seam were tested with one inch cubes being loaded normal to the bedding. The strength versus frequency diagram is shown in Figure 2.3 and, while varying seam strength is indicated by the results, there is considerable scatter and overlap of strength values between the three seams. The typical stress-strain curves were also recorded as shown in Figure 2.4.

Results of uniaxial and triaxial tests conducted on the No. 2 Seam at Wolvekrans Section Witbank Colliery were reported in a CSIR report (1965). This testing programme was conducted underground to overcome the effects on coal specimens resulting from the different underground and laboratory temperatures and humidity levels; the latter affects the moisture content which, it had been noted, affected test results. In addition, deterioration of the specimens through transportation could be minimized.

Triaxial compression tests were conducted on 1,6 inch diameter samples with a diameter to length ratio of 1:1,6. Specimens were loaded parallel and normal to the bedding. The results are shown in the Mohr diagram in Figure 2.5 and the Mohr envelopes were stated as being practically the same for all three length to diameter ratios. The uniaxial compression tests showed a 30 per cent decrease in strength from the specimens tested normal to the bedding to those tested parallel to the bedding. It is quoted that the strength obtained by Wiid (1963) of one inch cubes from the No. 2 Seam were about twice as strong as that obtained in this testing programme for the cylindrical specimens with a 1:1,6 width to length ratio.

Further work was reported by Bieniawski (1967b) on four one foot cubes and two 1,5 foot cubes in the Wolvekrans Section of the Witbank Colliery, Witbank Coalfield. Although not stated in the report, the tests are presumed to also have been conducted on the No. 2 Seam. The results are shown in Table 2.2.

TABLE 2.2 Experimental Results After Bieniawski (1967b).

Specimen Size	Specimen	Width (m)	Height (m)	Area m^2	Failure Load (kN)	Strength MPa
0,305 m cube	1	0,308x0,311	0,308	0,096	78,564	8,040
	2	0,305x0,308	0,298	0,094	72,824	6,564
	3	0,302X0,305	0,295	0,092	74,209	7,950
	4	0,308x0,302	0,298	0,093	88,543	9,384
			Average			7,984
0,457 m cube	I	0,445x0,447	0,457	0,203	131,816	6,448
	II	0,451x0,457	0,460	0,206	130,138	6,285

Bieniawski (1968d) summarized the results of testing specimens 0,75 to 60 inches cube. The results are shown in Table 2.3, apart from those samples larger than 18 inches cube which were tested in contact with the seam floor; these are discussed under the section on in situ tests. All the results were obtained in the Witbank Colliery, presumably in the No. 2 Seam. The effect of specimen size on strength is clearly seen in Figure 2.6, where a significant reduction in strength occurs with increasing specimen size; standard deviations of up to 27 per cent are quoted in some specimen sizes.

TABLE 2.3 Results of Underground Tests on Cubic Coal Specimens Loaded in Uniaxial Compression Perpendicular to the Bedding Planes, After Bieniawski (1968d).

Tests	Cubic Size (in)	Number Tested	Strength MPa	Deviation MPa	%
Underground	0,75	10	29,40	5,6	19
	1	10	32,80	4,8	15
	2	8	33,60	7,4	22
	2,7	5	31,50	8,6	27
	3	6	28,10	2,7	10
	6	7	12,80	3,0	24
	12	4	7,98	0,8	10
	18	2	6,27	0,1	1
In situ	24	1	5,52	-	-
	28	1	5,34	-	-
	36	2	4,89	-	-
	48	2	4,48	0,14	3
	60	2	4,44	0,14	3

Bieniawski (1968d) also stated that the strength of the 13 rectangular specimens, 3,5 x 2,0 inches and 2,0 inches high, was about 22,5 per cent higher than that of two inch cube specimens. A comparison of the strengths of 579 one inch cube specimens is given in Table 2.4, after Bieniawski (1968d), using a strength index based on the strength of the No. 4 Seam, Witbank Coalfield. This table shows that all other seam strengths are within 12,5 per cent of that of No. 4 Seam, with the exception of the No. 1 Seam (+45 per cent) of the Witbank Coalfield.