MINE	A
PANEL	12
DATE	15-10-81

PILLAR SIDES

☐	N	Straight cutter marks visible
☐	SL	Minor undulations 0,1 m
☒	M	0,1 - 0,3 m spalling
☒	S	0,3 - 0,7 m
☐	VS	> 0,7 m

CORNERS

☐	N	Square
☒	SL	0 - 0,5 m
☐	M	0,5 - 1,0 m
☐	S	1,0 - 1,5 m
☐	VS	>1,5 m

CRACK SIZE

☒	Tight	<0,5 mm
☐	Open	0,5 - 3,0 mm
☐	Moderately wide	3,0 - 10,0 mm
☐	Wide	10,0 - 30,0 mm
☐	Very wide	20,0 - 100,0 mm
☐	Extremely wide	>100,0 mm

STONE DUSTING

☒	C	Complete	80 - 100%
☐	W	Well	60 - 80%
☐	M	Moderate	40 - 60%
☐	SL	Slight	20 - 40%
☐	N	None	<20%

WEAKNESS IN PILLAR

☐	N	None	No sign
☐	SL	Slight	Signs of effect 0,1 m
☐	M	Moderate	0,1 - 0,3 m
☒	S	Severe	0,3 - 0,7 m
☐	VS	Very severe	>0,7 m

TIME SINCE LAST DUSTING

☐	One day
☐	One week
☒	One month
☐	One year
☐	More than one year

PILLAR - ROOF CONTACT

☒	VG	Very good	No signs of gap
☐	G	Good	Slight gap 2,0 mm
☐	F	Fair	2,0 - 10,0 mm
☐	P	Poor	>10,0 mm sides intact
☐	VP	Very poor	Spalling due to roof-pillar contact

STONE LAYER/WEAKNESS IN PILLAR

Present height from floor	2,4m
Band thickness	0,3m
Type of band	coal

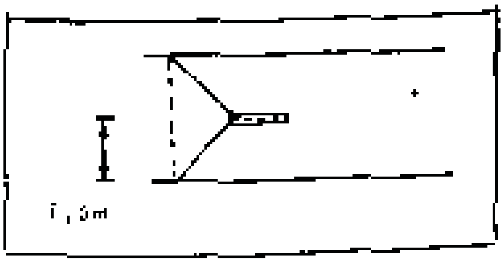
	IMMEDIATE ROOF	IMMEDIATE FLOOR
GEOLOGY THICKNESS	coal	sandstone

IS THERE PILLAR PUNCHING?

YES [✓ NO]

DESCRIBE:

SKETCH OF PILLAR, SHOW CRACKS AND DISTANCES



SKETCH OF CRACKS IN ROOF

nil

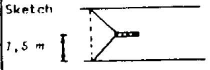
COMMENTS AND REMARKS e.g. where slabbing occurs.

Table 4.7 Assessment Form For Underground Pillar Condition.

MINE: *A*
SECTION: *No. 1 SHAFT*
SEAM: *I*

Area	*1 B*	Mining Method	*Drill and Blast*	Mined	*1978*	Age	*3 years*	Depth Max.	*104 m*	Depth Min.	*100 m*	Pillar Width	*17,8 m*	Bord Width	*6,9 m*
Seam height & max.	*4,0 m*	Seam height min.	*3,0 m*	Mining height	*3,5 m*	Top/Bottom Coaling	-	Pillar Extraction	-	Primary % Extraction	*47 %*	Secondary % Extraction	-	Primary Safety Factor	*2,40*
Secondary Safety Factor	-	Seam Above	*25 m*	Seam Below	-	Faults	-	Dyke Width	-	Dyke width min.	-	Dyke orientation	-	Distance to Sill	-
Falls in bord	-	Falls intersection	-	Falls area	-	Bord Fall Height	-	Intersection Fall height	-	Pillar Collapse	-	Area m^2	-	Surface Subsidence	-
Subsidence Depth	-	Panel Dimension	*200m x 700m*			Coal Deterioration	-	Roof Deterioration	-	Floor Heave	-	Burnt Coal	-	% loss due to Geology	-

Design comments

PILLAR CONDITION		Pillar width	*17,6 m*	Bord width	*6,9 m*	Height	*3,5 m*	Perimeter	-	Sides	*M-S*	Corners	*SL*	Sketch 
Dusting	*80 %*	Time since last dusting	*6 mths*	Pillar Punching	-	Floor Punching	-	Roof Punching	-	Weak layer in Pillar	*S*	Height from floor	*1,5 m*	
Stone layer		Height from floor	-	Floor Strata	*Sandstone*	roof	*Coal*	Weathering Floor	*Fresh*	Weathering Roof	*Fresh*	Photo No.	-	

Pillar condition comments: *good contact between roof and pillar. Pillars in some areas fritter at zone 3.*

SUPPORT		Type	Primary	Secondary	Area m^2	Pattern	Dimensions	Efficiency	Bolt Type	Length	Diameter	Falls	Falls height		
	Intersection	*Rockbolt*		-	*6,7 m^2*		*2,2 m x 2,0 m*	*100 %*	*Mechanical*	*1,8 m*	*16 mm*	-	-		
	Bord	*Rockbolt*		-	*6,7 m^2*		*2,2 m x 2,0 m*	*100 %*	*Mechanical*	*1,8 m*	*16 mm*	-	-		
	Pillar	-	-	-	-	-	-	-	-	-	-	-	-		

Support comments: *isolated minor falls.*

Discontinuities		Dip	Dip Direction	Regional Density	Local Density	Spacing	Persistance	Termination	Roof	Pillar	Effect on Pillar	Roughness	Support	Water	Shape of Bord
Type		↑													
		minor													
		↓													

Only minor discontinuities No effect on pillar.

Assessment of Pillar.
Pillars in good condition . very few slips . Zone 3 spalling evident.
Moderate spalling of pillar sides.

Table 4.8 Summary of Pillar Classification.

Pillar Rating Seam: I Date: 15/10/81 Age: (t) 3 yrs.

Pillar Condition

SLABBING AS A % OF MINING HEIGHT

Sides		Corners	
0 - 5 %	100	0 - 10 %	100
5 - 15 %	75 ◀	10 - 25 %	75
15 - 30 %	50	25 - 40 %	50 ◀
30 - 50 %	25	40 - 55 %	25
> 50 %	0	> 55 %	0

DISCONTINUITY EFFECT ON PILLAR

None		
Slight	Minor effect on one corner or side	100 ◀
Moderate	Major effect on corner or side	75
Severe	Major effect on several corners or sides	25
Very Severe	Feature reduces pillars area by 30 %	0

Pillar Condition (R_0) 360
×
Time Factor (T_f) 1,29
Pillar Rating (R_I) = 465

WEAKNESS IN PILLAR

None	20
Slight	15
Moderate	10
Severe	5 ◀
Very Severe	0

COAL WEATHERING

> 1 yr	20
1 - 12 mth	15 ◀
1 - 4 weeks	10
1 - 7 days	5
< 24 hours	0

PILLAR PUNCHING

None	100 ◀
Slight	75
Moderate	50
Severe	25
Very Severe	0

STONE DUSTING				TIME SINCE DUSTING		
Complete	80 - 100 %	20 ◀		> 1 yr	1,00	
Well	60 - 80 %	15		1 - 12 mth	0,75 ◀	
Moderate	40 - 60 %	10	X	1 - 4 weeks	0,50	15
Slight	20 - 40 %	5		1 - 7 days	0,25	
None	< 20 %	0		< 24 hours	0	

Roof Condition

PILLAR - ROOF CONTACT

Very Good	No signs of gap	100 ◀
Good	Slight gap 2,0 mm	75
Fair	2,0 - 10,0 mm	50
Poor	>10,0 mm sides intact	25
Very Poor	Spalling due to roof-pillar contact	0

WEATHERING

Fresh	20 ◀
Moderate. High strength	15
Moderate. Low strength	10
Slabbing	5
Rapid deterioration	0

ROOF COMPETENCE

No falls/cracks	20 ◀
No falls but cracks	15
Occasional minor falls	10
Falls to competent layer	5
Falls to an incompetent layer	0

IMMEDIATE ROOF STRATA THICKNESS

> 2,0 m	20
2,0 - 1,5 m	15
1,5 - 1,0 m	10
1,0 - 0,5 m	5 ◀
< 0,5 m	0

HEIGHT OF FALLS

Nil	20 ◀
Slight	15
Moderate	10
Severe	5
Very Severe	0

Roof Condition Rating $\frac{165}{180}$

Roof Falls

DENSITY OF FALLS			EXTENT		
None	100		Nil	1,0	
Occasional on a slip or dyke	75 ◀		Minor < 0,3 m	0,75 ◀	
Associated with slips or dykes	50	X	0,3 m - 1,0 m	0,50	56
Intersections only	25		1,0 m - 2,0 m	0,25	
Intersections and bords	0		> 2,0 m	0	

Dyke ◀
Slip ◀
Fault
Incompetent roof

Roof Falls Rating $\frac{56}{100}$

Support Type

(A)			(B)			(C) DENSITY			(D) EFFICIENCY		
None	100		Wire Mesh	5		None	20		90 - 100 %	1,00 ◀	
Rock Bolt	50 ◀	+	Other	5	+	> 6 m^2	15 ◀	X	80 - 90 %	0,75	65
Timber	40					3 - 6 m^2	10		70 - 80 %	0,50	
Other	0					1,5 - 3 m^2	5		50 - 70 %	0,25	
						<=1,5 m^2	0		< 50 %	0	

(E) SIDE SUPPORT		(E x D)
None	20 ◀	
> 10 m^2	15	20
5 - 10 m^2	10	
< 5 m^2	5	
< 5 m^2 + Other	0	

Support Rating $\frac{85}{140}$

DISCONTINUITIES

PERSISTANCE

Very Low	< 1,0 m	20 ◀
Low	1,0 - 3,0 m	15
Medium	3,0 - 10,0 m	10
High	10,0 - 20,0 m	5
Very High	> 20,0 m	0

REGIONAL DENSITY

Rare	20
Random, isolated	15 ◀
> 100 m apart	10
30 - 100 m	5
< 30 m	0

LOCAL DENSITY

None	20
Slight	15
Moderate	10 ◀
Dense	5
Very Dense	0

WATER

None	20 ◀
Moist	15
Drip	10
Flow	5
Flow > 5 ℓ/min.	0

Discontinuity Rating $\frac{65}{80}$

Table 4.9 Pillar Rating Form.

4.3.3 Results

Pillar conditions in seven different coal seams have been assessed using the visual method described in this chapter. Details of the more important mining parameters and the number of workings examined in each seam are given in Table 4.10. It can be seen from this table that about half of all cases belong to Seam I. Only a limited number of old workings were accessible in Seams V, VI, and VII. Wherever feasible, workings in a particular seam were selected to cover as wide a range of safety factors as possible.

Table 4.10 Range of Pillar Workings Covered by Investigation.

Seam	Depth (m)			Mining Height (m)			Safety Factor			Number of cases
	min	av	max	min	av	max	min	av	max	
I	32	73	123	2,1	3,8	6,4	1,1	1,8	4,0	58
II	33	50	76	2,2	3,0	5,0	1,2	1,6	2,5	21
III	30	50	60	1,5	2,0	2,4	1,9	2,4	3,4	10
IV	60	103	123	2,4	2,8	3,6	1,8	2,0	2,1	11
V	72	83	112	1,5	2,7	4,2	1,4	1,9	2,4	7
VI	45	48	53	1,6	1,9	2,3	3,3	3,6	4,4	4
VII	85	85	85	2,0	2,0	2,1	2,4	2,7	3,1	3

In the analysis of the pillar ratings, only cases older than two years were used, as the rock strength is time dependent.

Figure 4.5 shows the relationship between the average pillar stress and the pillar rating for Seam I. In addition to the quantitative rating, a qualitative indication of pillar condition is given. For example "poor" relates to excessive slabbing of coal from pillar corners and pillar sides and the presence of joints and slips in the seam. According to Figure 4.5, there is a well defined correlation between the average pillar stress and the pillar conditions. This trend can be described by the following equation:

$$R_l = 1021 - 93.7\sigma, \tag{4.3}$$

where σ is the average pillar stress.

For Seam II the corresponding equation is:

$$R_{II} = 1084 - 109\sigma. \tag{4.4}$$

As is to be expected with geological materials, there is a relatively wide spread of data points. However, there is a statistically significant trend in that the pillar rating increases with decreasing pillar stresses. In terms of the rating system high pillar rating indicates good pillar condition. Pillar ratings below 400 are indicative of excessive spalling of coal from pillar sides and, therefore, generally very poor conditions. In contrast, a pillar rating in excess of 600 relates to excellent conditions with a minimum amount of spalling of coal from pillar corners and no visible signs of pillar deterioration. A rating of about 525 refers to average conditions with about 0,1 to 0,3 m of spalling of coal from the pillar sides and a slight rounding of pillar corners. It should be noted that two workings which were rated below 350 have subsequently failed.

Table 4.11 gives a summary of the average pillar stresses and pillar ratings for the seven coal seams, and shows that, with the exception of Seams III, VI and VII, the average pillar stresses fall within the relatively narrow range of 5,0 to 5,8 MPa.

Table 4.11 Summary of Average Pillar Stresses and Pillar Ratings for Seven Coal Seams.

Seam		I	II	III	IV	V	VI	VII
Observations		48	20	6	10	6	4	3
Average Stress								
Mean (MPa)		5,03	5,36	4,48	5,50	5,79	3,52	4,68
Standard Deviation		0,99	0,94	0,73	0,62	0,27	0,38	-
Standard Error (95% Confidence)		0,14	0,21	0,30	0,20	0,11	0,19	-
Upper Limit		5,32	5,81	5,26	5,95	6,07	3,52	4,68
Lower Limit		4,74	4,91	3,71	5,05	5,52	3,51	-
Rating								
Mean (MPa)		441,4	402,9	456,8	375,4	456,3	492,0	471,0
Standard Deviation		44,4	38,8	35,9	44,4	18,9	4,4	29,5
Standard Error (95% Confidence)		6,4	8,9	14,6	14,0	7,7	2,2	17,0
Upper Limit		454,3	421,6	494,5	407,2	476,2	492,1	541,8
Lower Limit		428,5	384,2	419,2	343,6	436,5	491,9	398,2
Relative Variation	Stress	19,7%	17,5%	16,3%	11,3%	4,7%	10,8	-%
	Rating	10,1%	9,6%	7,9%	11,8%	4,1%	0,9%	16,0%

Figure 4.6 shows the average pillar ratings for the seven coal seams. For reference purposes the pillar rating curve for Seam 1 is given.

According to Figure 4.6, all but one of the seams (Seam IV) are grouped in a narrow band and fall in the range of fair to good pillar conditions. The average pillar rating of Seam IV is substantially lower than that of the other seams. Other interesting observations are that the average pillar stresses are distinctly different in Seams V, VI and VII which have nearly identical ratings. For example, the average pillar stress in Seam V is about 1,5 times the average pillar stress in Seam VI and yet the pillar ratings are about the same. This suggests that Seam VI is weaker than Seam V.

As all workings are designed according to a well established procedure, the close rating of most of the seams suggests that there is a small deviation in individual seam strength. Furthermore, it has been a tendency in the mining industry to adjust pillar design safety factors to local variations in seam conditions. Pillar conditions in Seam IV are known to be poor and many of the more recent pillar failures occurred in this seam. However, it must be pointed out that, because of the depth of Seam IV, the average pillar stresses tend to be somewhat higher than in most other seams. This is obviously a contributing factor and needs to be considered when assessing the strength of the different coal seams.

Before addressing the question of individual coal seam strength, some aspects of the average pillar ratings in the individual seams should be examined. Basically the pillar rating comprises four different components, namely, an assessment of the amount of fracturing that has taken place, an assessment of geological features that may influence pillar conditions, an assessment of the amount of pillar punching that has taken place and, finally, an assessment of pillar deterioration over time. Table 4.12 gives a summary of the contribution of these four components to the overall pillar rating. It follows from the tabulation that the influences of pillar punching, stone dusting and time on the overall pillar rating can be ignored since their contributions are either equal or negligible. This leaves the extent of slabbing of pillar corners and sides and the geological factors as the main parameters which control the overall pillar rating. The variations in the geological ratings are 20 per cent between Seam IV, which rates low, and Seams III, V, VI and VII, which are virtually free of geological weaknesses. As far as pillar fracturing is concerned, Seams I, II, III and V rate very favourably while Seams VI and VII rate as average and Seam IV rates below average. It follows from this comparison that Seam IV rates poorly on both counts, while in the case of Seams III and V both the geological and fracture ratings are high. An interesting observation is that Seams VI and VII have a rather poor stress rating despite very favourable geological conditions and relatively moderate stress levels. This suggests that the strength of these two seams is below average.

TABLE 4.12 Pillar Ratings for Seven Coal Seams Separated into Pillar Conditions, Geological Parameters, Pillar Punching and Time Factor.

Seam	I	II	III	IV	V	VI	VII
Observations	48	20	6	10	6	4	3
Sides	95	89	83	622	92	81	67
Corners	71	60	70	40	67	44	58
Pillar Rating	166	149	153	102	159	125	125
Slips	90	87	95	85	100	100	100
Weak Layer	18	16	20	11	20	20	18
Coal Weathering	19	19	20	14	20	20	18
Geological Rating	127	122	135	110	140	140	136
Pillar Punching	97	97	100	100	100	100	100
Stone Dust	6	7	9	3	10	10	5
Total Rating	386	375	377	315	408	375	366
Time Years	13	10,6	15	3,9	4,6	14,75	16,35
Time Factor	1,4	1,384	1,412	1,31	1,317	1,41	1,418
Rating x Time Factor	554	519	560	412	538	528	519

As a first step in rating the relative strength of the various coal seams, the rating of Seam I, which is based on 48 observations, can be taken as a reference. (In this connection it should be noted that most of the case studies from which Salamon and Munro (1967) derived their pillar strength formula came from Seam I.) On this basis it is found that Seam V is stronger than Seam I, while Seam II is of slightly lower strength. All other seams are rated as having a lower strength than Seam I. In general, the variations in coal seam strength appear to be rather small and are of the order of 0,1 to 0,2 of the strength of Seam I. The only exception is Seam IV which appears to have a significantly lower strength than Seam I.

Because of the strong sensitivity of the pillar rating to average pillar stresses, a small variation in pillar stress can result in a significant change in rating. Thus the slope of the reference rating line becomes extremely critical, particularly for the assessment of the actual strength differences between Seams I and IV which were rated significantly differently.

A major limitation of the classification system was access to panels mined in excess of two years ago. Old workings are sealed for ventilation purposes and, as the main developments are often designed to a safety factor in excess of 2,0, the pillars formed had high width to height ratios. This lack of data was apparent when plotting pillar rating versus average pillar stress for Seams III, V, VI and VII.

4.3.4Conclusion of Classification System

The visual method of assessing the condition of coal pillars has been shown to be a useful tool in determining the relative strength properties of the different seams. Because of the strong dependence of pillar rating on the average pillar stress, the method is very sensitive to the slope of the pillar rating curve for the reference seam. An accurate comparison of coal seam strength properties requires that the observations of pillar conditions cover a wide range of average pillar stress values. Unfortunately, the depth range of the individual seams covered by this investigation was rather narrow. This has limited the application of the visual method.

4.4 CONCLUSIONS

Adding the 17 collapsed pillar cases that occurred between 1966-1988 to the cases used by Salamon and Munro (1967), and applying the same statistical method, showed a variation in the values for k, α and β. However, calculations using these parameters showed little strength variation between width to height ratios 2,5 to 6,0 for the 1904-1966 cases and the 1904-1988 cases. At lower width to height ratios an increase in the strength required was obtained for the 1966-1988 collapsed cases which reflects the fact that low width to height ratios pillars are prone to collapse. It is suggested that the parameters obtained by Salamon and Munro for k, α and β be maintained, and when designing low width to height ratio pillars the recommendations of Chapter 3 be adhered to as these will account for the variations in coal structure and human error.

Applying the statistical analysis to individual seams showed that there was no statistically significant difference in seam strength using this method. The reason for this may be that the number of cases in individual seams were insufficient to give meaningful results or that coal, as a material, varies such that an average value can be designated for coal strength provided that the sample's volume is sufficiently large so as to represent full size pillars.

The visual classification system developed for the assessment of pillar performance indicated strength differences. However, the classification was limited by its sensitivity to average pillar stress and lack of data owing to inaccessible panels or pillars having high width to height ratios. The classification system showed that the strength of all seams were within 0,1-0,2 times the No. 2 Seam of the Witbank Coalfield with the exception of the No. 3 Seam of the Orange Free State Coalfield. Therefore, when designing pillar geometries one average strength can be used for all seams but it is suggested, in the case of the No. 3 Seam of the Orange Free State Coalfield, that a higher safety factor, in excess of the normal 1,6 and closer to 2,0, is used.

It is concluded from this investigation that one average strength of 7 176 kPa can be used in the Salamon and Munro strength formula for all seams in South African collieries and that the strength variation between individual seams is limited.

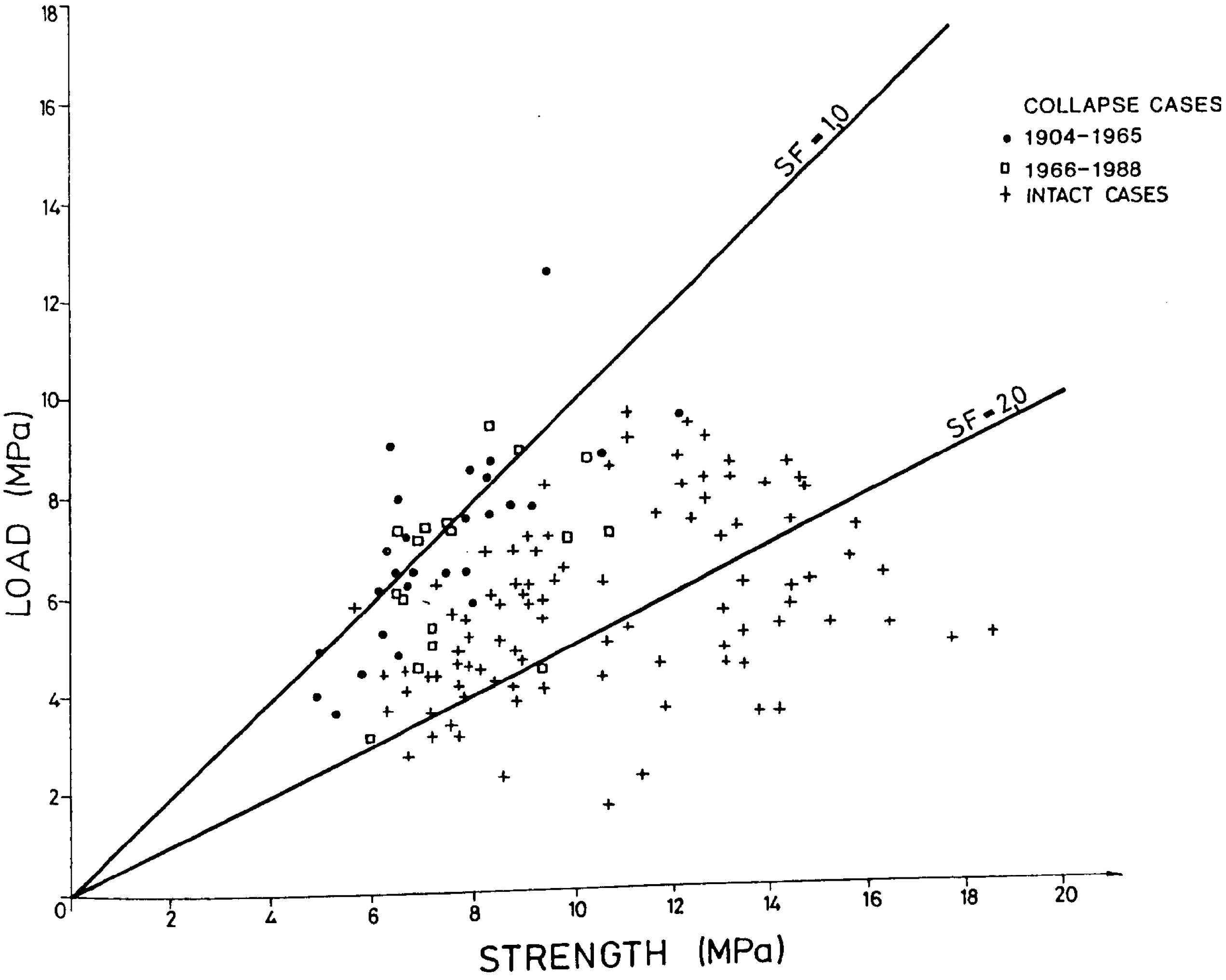


Figure 4.1 Load versus strength of collapsed pillar geometries.

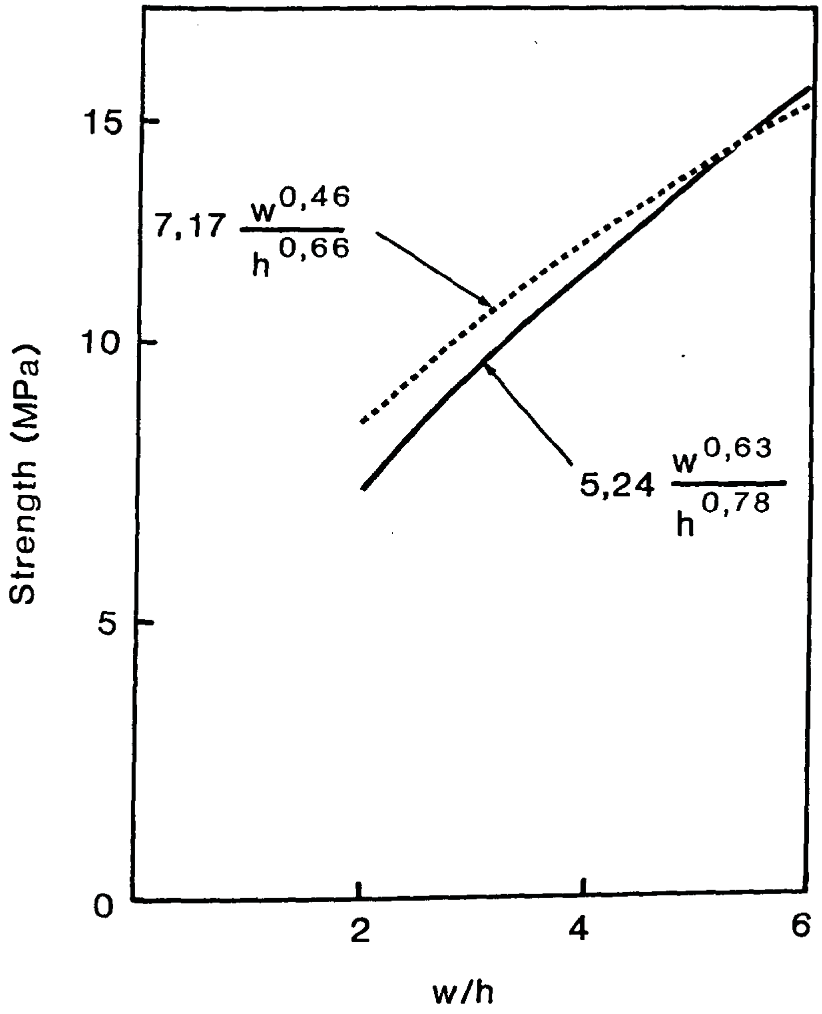


Figure 4.2 Strength versus pillar width to height ratio using the calculations of Salamon and Munro (1967) and those derived from the statistical analysis which includes all collapsed pillar cases between 1904 and 1988.

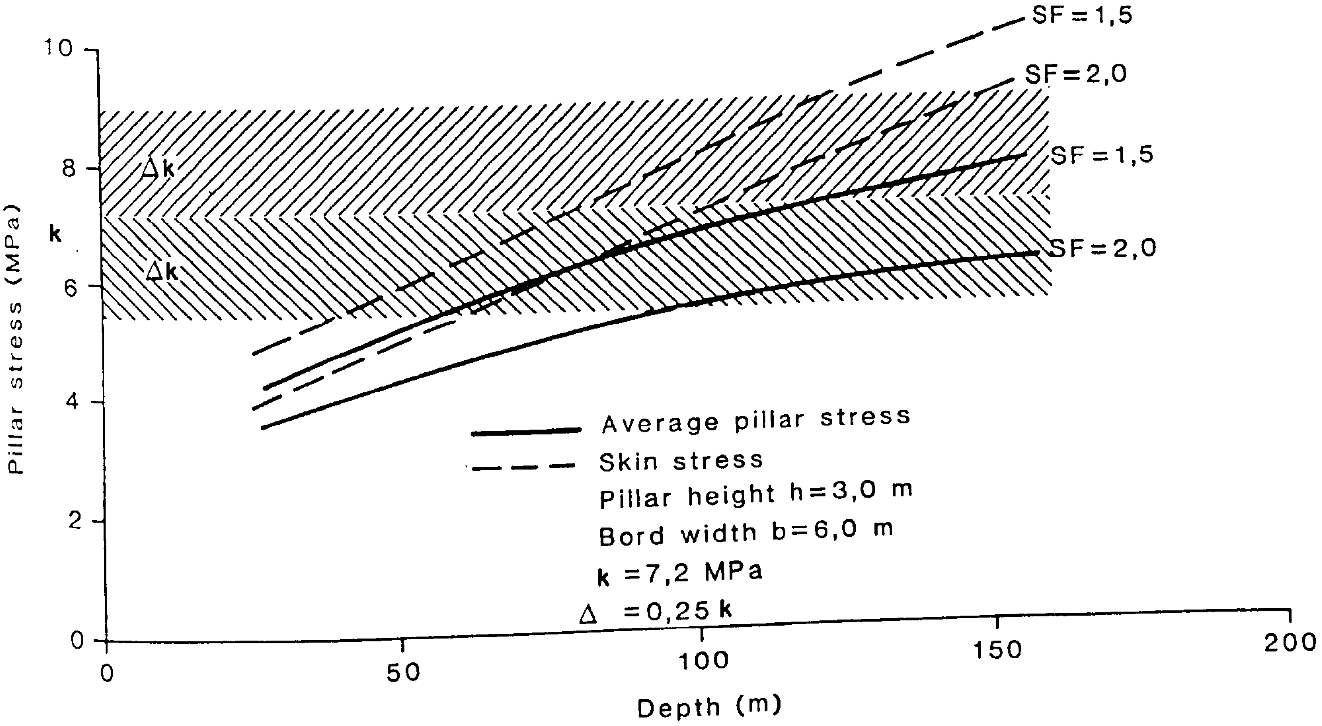


Figure 4.3 Relationship between depth of mining and pillar stresses for two different safety factors.

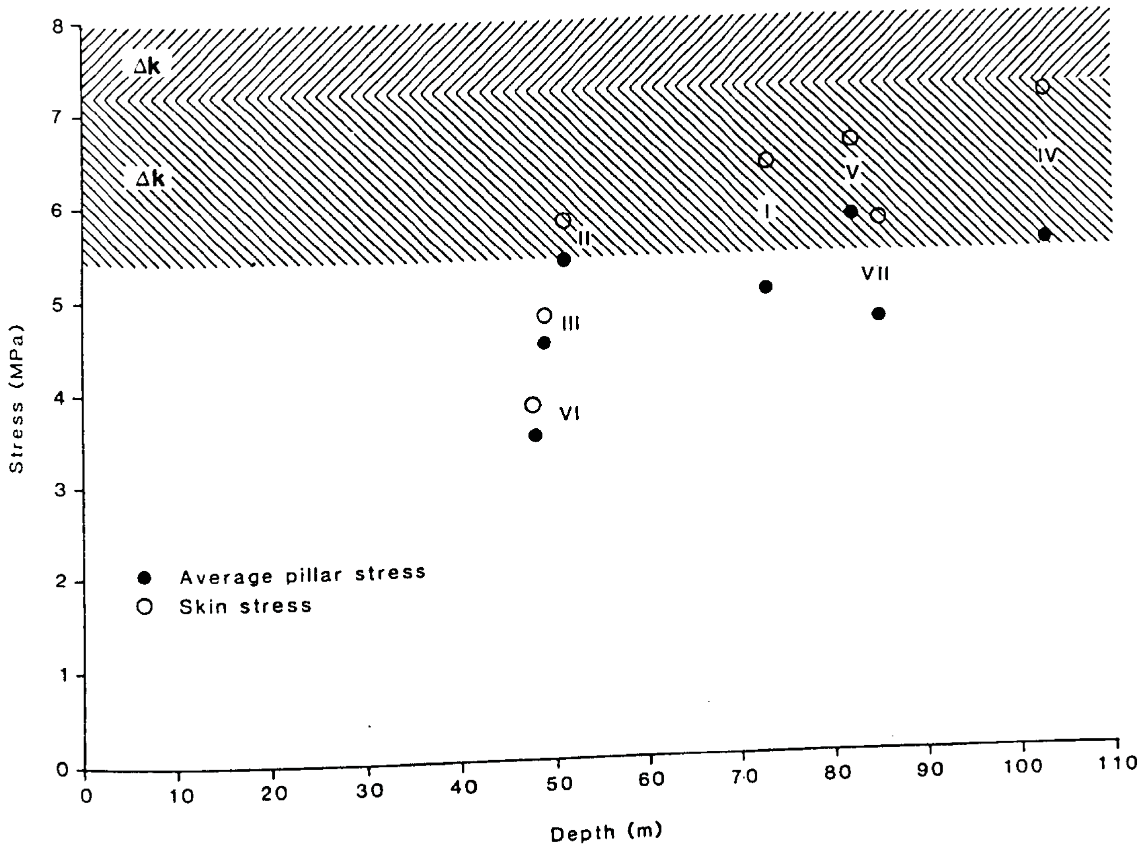


Figure 4.4 Pillar stresses for seams covered by the survey.

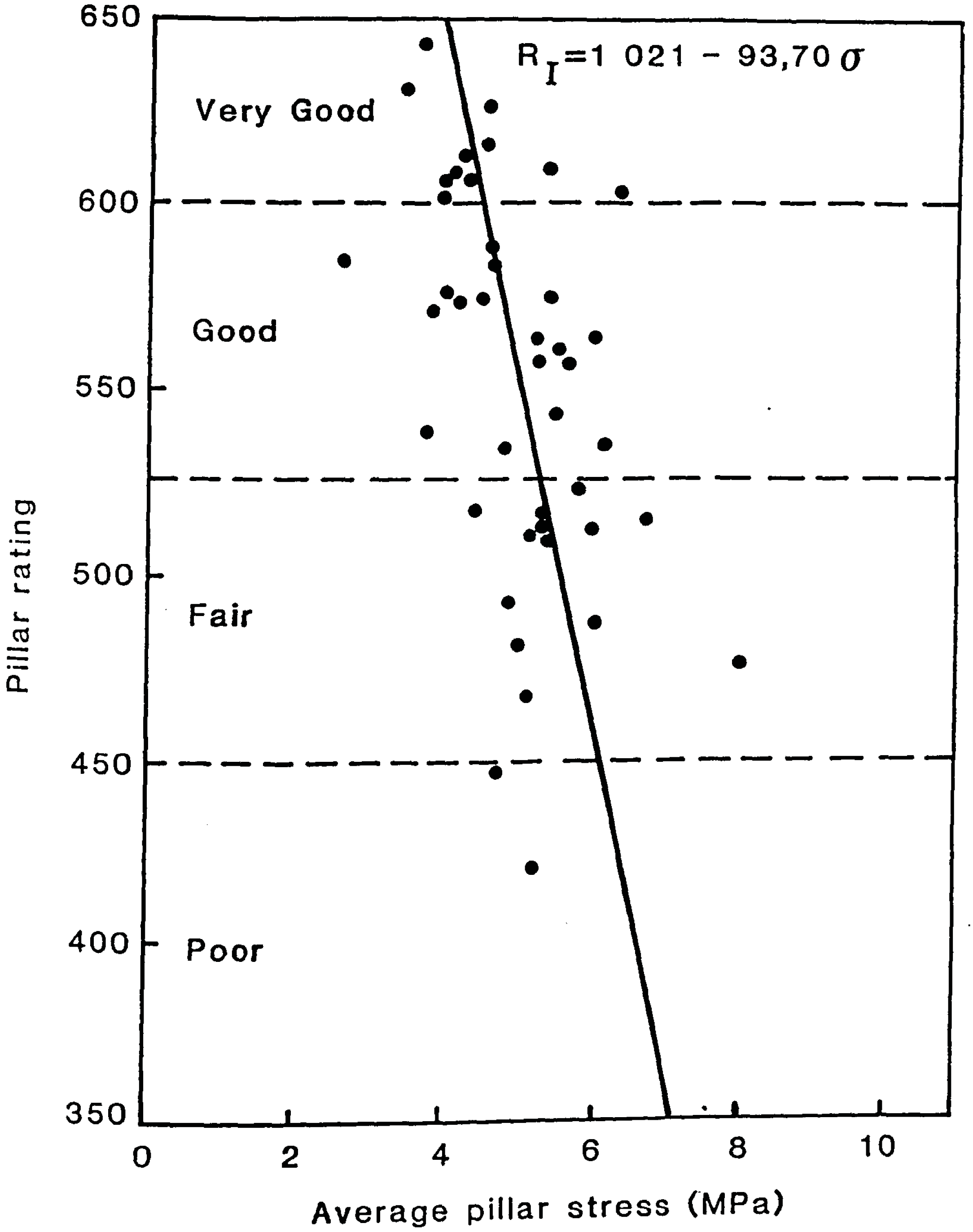


Figure 4.5 Average pillar stress (MPa) and pillar rating for Seam I.

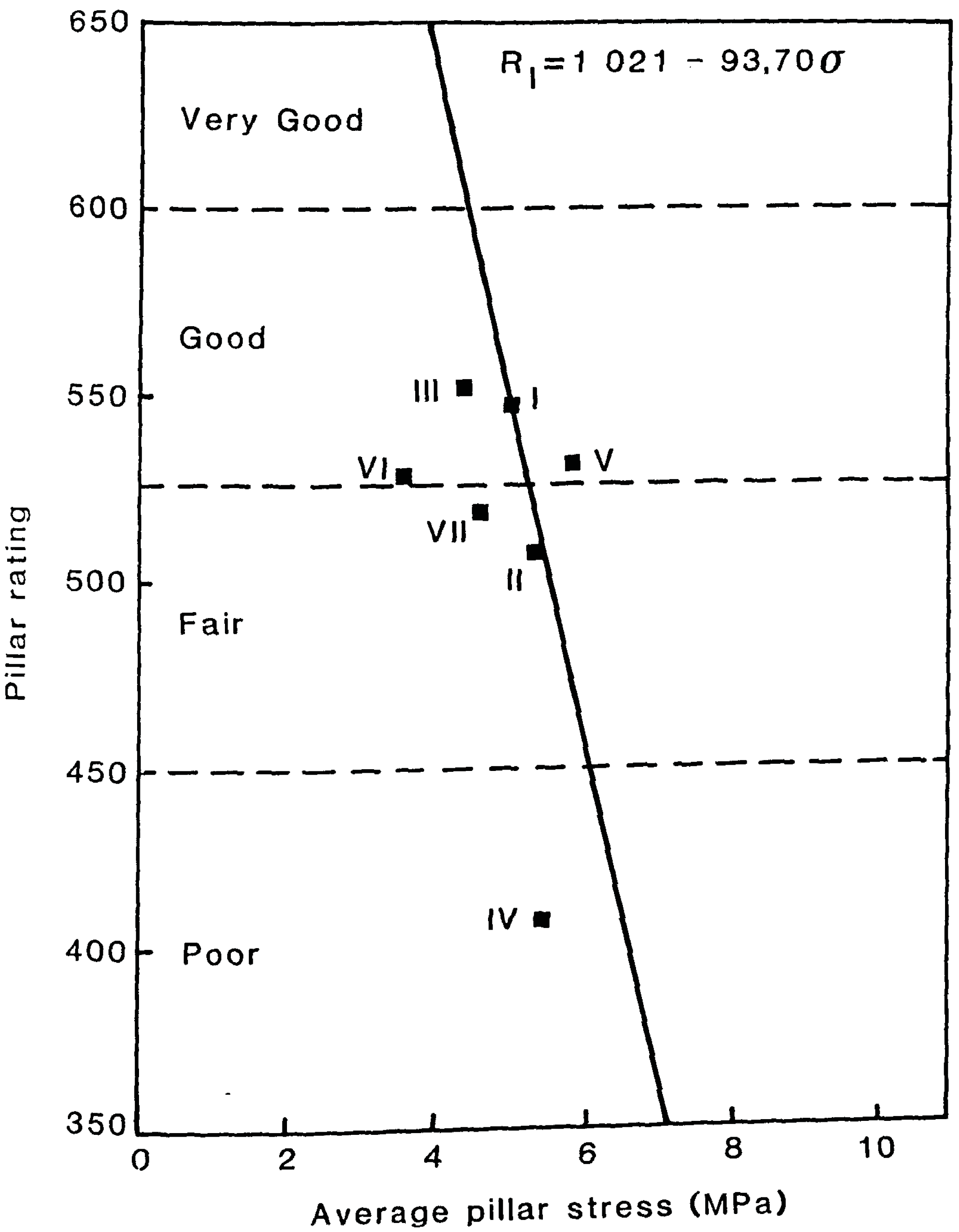


Figure 4.6 Average pillar stress (MPa) and pillar rating for seven seams.

CHAPTER 5

THE EFFECT OF MINING METHOD ON PILLAR STRENGTH

5.1 INTRODUCTION

Blast vibration and the penetration of the gases from explosions into existing discontinuities damage the skin of a coal pillar formed by conventional drill and blast techniques. The fracturing thus caused reduces the strength of the perimeter of the pillar resulting in a zone of weakness which is not present in pillars formed by continuous miners. This weakened zone spalls from the pillar side with time and reduces the width of the coal pillar.

The pillar design formula of Salamon and Munro (1967) is based on a statistical analysis of case histories of bord and pillar workings, all of which were mined using the drill and blast method. The analysis is based on the designed mining dimensions which means that the derived coal pillar strength formula indirectly takes into account the weakening effect of blast damage. Therefore, the effective width of a pillar, designed according to the present design formula but mined by a continuous miner, must be greater by an amount approaching the extent of the blast zone than that of a pillar formed by drilling and blasting, Figure 5.1.

Around 75 per cent of all coal produced by underground mining methods in the Republic of South Africa is mined by the bord and pillar method of extraction. Continuous miners are responsible for approximately 25 per cent of this figure. This means, therefore, that a large volume of coal may be unnecessarily left in coal pillars which are designed using the present pillar design formula.

The results of experiments conducted at Cornelia and Kriel Collieries are presented in this chapter and are used to compare the condition of pillars in sections mined by continuous miners to that of pillars in sections mined by conventional drill and blast methods. The objective of this investigation was twofold, namely:

(i) to determine the extent of blast damage in a pillar formed by drill and blast methods, and
(ii) to determine the effect of time on the condition of pillars formed by the two methods.

By meeting these two objectives, the experiments should lead to the design of pillars for continuous miner operations which is not only safe but will also yield an increase in percentage extraction.

5.2 BLAST DAMAGE AROUND A CHARGE HOLE

5.2.1 Conventional Blasting Practice

Typically, a coal face in conventional drill and blast bord and pillar workings is 6,0 m wide and between 1,0 and 4,0 m high, and is drilled on a 15 hole pattern by electric face drills, Figure 5.2. The holes are approximately 2,6 m long and roughly perpendicular to the face. Blast holes on the perimeter are approximately 0,15-0,2 m from the final pillar position. A slot, or second free face, around 2,7 m long and 0,15 m wide, is cut by the coal cutter over the entire face width, usually about 0,8-0,9 m from the floor. The normal hole charge consists of four 0,2 kg sticks of explosive. A blasting cap is inserted into the explosive, with the hole timing dependent on local conditions and colliery standards. Stemming is placed into the hole to provide confinement.

5.2.2 Detonation Process

Detonation of the explosive charge produces gas at a very high temperature and pressure which rapidly fills the borehole and exerts relatively constant pressure over the length of the borehole causing it to expand suddenly. The outward acceleration of the borehole generates a strain wave which propagates in a radial direction through the surrounding rock. Planar fractures initiated by this wave extend in all radial directions from the blast hole causing radial fracturing. The high radial compressive stresses cause crushing and the tangential stress causes radial fracturing of the rock. Harries (1973) states that as the maximum crack propagation speed is 0,38 times the longitudinal wave (sonic), the extent of radial cracking due to the strain wave is limited. However, the expanding gases in the borehole stream into the cracks formed by the strain wave enlarging and extending them through pneumatic wedging. Radial strain waves are reflected in tension from the free face and may result in further crack propagation.

5.2.3 Blast Damage Zone

During detonation and expansion of the explosive gases, several zones of blast damage are created. Figure 5.3 illustrates a blast hole, assumed to be at mid-pillar height and on the edge of the blasting pattern, and the blast damage around the borehole and into the pillar side. In the immediate vicinity of the blast hole, the rock is severely cracked and may be crushed. The extent of the crushed zone is between one and two borehole radii, Langefors and Kihlstrom (1967).

The radial cracks formed by the strain wave, and possibly by the expanding gas, decrease with increasing distance from the blast hole. Part of this blast-induced damage breaks away during the blast, but blast-induced cracks also extend into the pillar. It is this zone of weakened coal which remains attached to the pillar that is termed the "blast damage zone".

Slabbing of the blast damage zone may occur through subsequent blast vibration or as load is taken up by the formation of the pillar. As the material strength of coal is also affected by time, part of the weakened blast damage zone may slab only after a period of time. As a result of the fractures induced in this zone, weathering of the skin of a coal pillar may proceed at an accelerated rate, and ultimately most of this damaged surface will fall away.

5.2.4 Effect of Geology

Existing discontinuities within the rock mass can influence the formation of the blast damage zone by terminating the radial fractures. This can occur by the existing discontinuity either providing the expanding gases with an escape route or acting as openings in the rock mass which cause the strain wave to be partly reflected on their surface. As a result of the heterogenous nature of coal some layers will be more susceptible than others to the propagation of radial cracking.

5.3 METHOD OF INVESTIGATION

5.3.1 Quantifying the Blast Damage Zone

Direct measurements of blast-induced fractures in the perimeter of coal pillars formed by conventional drilling and blasting are possible. However, some parts of the weakened blast damage zone may spall from the pillar sidewall with time. Therefore, to evaluate the effect of time, it was necessary to compare measurements made in areas mined several years ago to those made in recent workings. Ideally, sections mined to the same depth and safety factor under similar geological conditions would provide the best comparison.

5.3.2 Observation Holes

Observation holes were drilled in pillars in the centre of each panel, away from the influence of barrier pillars, and the depth of the fractures in the pillar side were measured using a petroscope. A minimum of 10 pillars in each panel were drilled at mid-height in the patterns shown in Figure 5.4, and a minimum of four pillars in the eight hole pattern. The latter was done to investigate the extent of fracturing in the pillar corners and to compare the condition of the corners with that of the pillar sides. Washing of the observation holes removed the fines caused by drilling, making the cracks more visible.

5.3.3 Petroscope

Initially, the fractures were measured using an optic-fibre petroscope. However, this instrument had several operating problems including the length of observation being limited to 2,5 m. In addition the illumination, provided by a miner's cap lamp, made correct light focusing difficult, while the instrument's small observation area made interpretation of features difficult and several hours of observation strained the user's eyesight.

A petroscope, made by COMRO (Chamber of Mines Research Organization), Figure 5.5, overcame many of these operating problems. The area of observation was 19 times larger than that of the optic-fibre instrument facilitating interpretation of the features. Observation of features beyond 1,0-1,5 m into the pillar side required magnification and the assistance of a surveyor's level proved ideal.

5.3.4 Bord Measurements

Blast damage induces both spalling and fracturing of the pillar side. Therefore, pillars mined by drilling and blasting should show an increase in bord width over time, which should not be apparent in pillars mined by continuous miner. Bord measurements were taken from the centre of the pillar at mid-height and, for statistical reasons, more than 150 measurements were taken in each panel.

5.4 EXPERIMENTAL SITES

5.4.1 Location

The investigation was conducted in the Top Seam at Cornelia Colliery in the Vaal Basin and in the No. 4 Seam at Kriel Colliery in the Witbank Coalfield.

5.4.2 Cornelia Colliery

Production panels at the South-East Shaft of Cornelia Colliery were ideally suited for the investigation of blast damage zones because of their close proximity to previously and recently mined panels formed by both mining methods. Figure 5.6 shows the panels investigated. The 200 Main was mined partly by conventional drill and blast methods and partly by a continuous miner.

Table 5.1 Nominal Design Dimensions of Panels Investigated at Cornelia Colliery.

	CM Recent	CM Old	D&B Old	D&B Recent
Depth (m)	105	105	109	113
Pillar width (m)	10,0	14,2	14,5	14,1
Centres (m)	16,0	20,0	20,0	20,0
Mining height (m)	2,9	3,0	2,75	3,0
SF	1,5	2,3	2,5	2,0

D&B	Drill and Blast
CM	Continuous Miner
SF	Safety Factor

The borehole logs to the south of the investigated panels recorded a dolerite sill of around 20 m thick, Figure 5.7a, while to the north, Figure 5.7b, no dolerite sill existed. However, since the dolerite was very close to surface, and probably partially weathered, its effect on the pillars is considered insignificant. In addition, the triangular shaped panel next to the experimental panel had been totally extracted, and the sill in this region had probably failed. For these reasons it was assumed that pillars in the experimental section were subjected to the full overburden load.

5.4.3 Kriel Colliery

Four panels were required for the investigation and it was necessary to select sections in different locations in the mine, which meant that their mining depths varied. Figure 5.8 shows the panels investigated. Table 5.2 summarizes the dimensions of the pillars in these panels.

Table 5.2 Nominal Design Dimensions of Panels Investigated at Kriel Colliery.

	D&B Old	CM Old	D&B Recent	CM Recent
Depth (m)	60	76	56	53
Pillar width (m)	9,6	9,6	7,6	8,6
Centres (m)	16	16	14	15
Mining height (m)	3,8	3,8	3,8	3,8
SF	2,0	1,6	1,6	2,0

D&B	Drill and Blast
CM	Continuous Miner
SF	Safety Factor

No significant variation in the geology of the overlying strata occurred and the generalized geological log is shown in Figure 5,9.

5.5 RESULTS OF INVESTIGATION

5.5.1 Cornelia Colliery

5.5.1.1 Results of fracture measurements

Figure 5.10 summarizes the depth and frequency of fractures in the pillar sides. It can be seen that in the recent pillars mined by drill and blast methods, fractures with a maximum depth of 0,23 m were present in approximately half the observation holes. The average depth of fracturing was 0,11 m.

In the continuous miner formed panel mined three to four years previously, there were virtually no fractures present in the observation holes. Fractures were not observed in the recently mined continuous miner panel up to 12 months after mining, but did occur in pillars observed between 12 and 18 months after mining.

5.5.1.2 Results of bord measurements

Figure 5.11 shows bord measurements taken from a recent section and from a section mined three to four years previously. Both sections were mined by drill and blast methods. Measurements taken by the surveyor of bord width in the recently mined section agreed with those taken by the author during the investigation. However, in the panel mined three to four years previously, the bord width had increased by an average of 0,5 m over the surveyor's original offset.

Similar plots are shown in Figure 5.12 for the recently mined and for the three to four year old continuous miner sections. The bord width of the latter had increased by an average of 0,14 m over the former. This increase may, however, be a result of human error in measuring the bord widths, or weathering of the coal or a combination of both.

5.5.1.3 Computer analysis of pillar stress

The mining dimensions were analysed on a computer to determine the stress levels on the pillars and hence assess whether the fractures observed could have been induced by stress acting on undisturbed coal of the pillar sides and corners.

Using the method described in Section 4.3.1 the results from the two-dimensional computer program MINAP gave the stress distribution across a pillar width as shown in Figure 5.13. In the model each pillar was divided into elements. The results obtained at the mid-point of each element were joined together for a comparative assessment of results. The pillar dimensions used are approximately those of drill and blast formed pillars and three to four year old pillars formed by a continuous miner.

Assuming that the strength of a unit cube of coal is 7,2 MPa, stress-induced fractures would not be anticipated in pillars mined by the drill and blast method at the depth of the panels investigated. Therefore, any fracturing of the pillar or decrease in pillar width should be a result of to blast-induced damage.

5.5.1.4 Summary of Results from Cornelia Colliery

The increase in bord width from blast damage to the perimeter of the pillars mined by drill and blast methods is approximately 0,5 m. The fractures observed into the pillar side extend over a distance of around 0,1 m. Therefore, the blast damage zone of pillars mined by conventional drill and blast operations extends approximately 0,3 m into the pillar side at Cornelia Colliery.

The pillar condition in all panels could be described as very good, according to the pillar classification described in Chapter 4; this is despite the approximately 0,25 m of spalling observed in the panel mined by drill and blast methods three to four years earlier.

5.5.2 Kriel Colliery

5.5.2.1 Results of Fracture Measurements

Figure 5.14 summarizes the maximum depth of fractures and number of holes recording fractures in the pillars. Fractures were present in one third of the observation holes in the pillars mined recently by drill and blast methods and extended to a maximum depth of 0,46 m. In the six year old workings, half of the holes had fractures to a maximum depth of 0,52 m. The average depth of fracturing in both sections was about 0,2 m into the pillar side. These measurements refer to the fractures in the pillar side and not in the corners.

Pillars mined recently by continuous miner had virtually no fractures in the pillar sides or corners. In the three to four year old continuous miner formed panel, seven of the 56 observation holes showed fractures, the deepest fracture being 55 mm into the pillar side.

Figures 5.15-5.18 show the frequency and extent of fracturing in the different panels. Observations of fractures in the drill and blast formed pillars show that the more severe fractures extending into the pillar are not necessarily in the corners. Fractures in the pillar sides are of the same order as in the corners.

5.5.2.2 Bord measurements

Figure 5.19 shows bord measurements for the panels mined by drilling and blasting. The bord width increased by an average of 0,47 m over the period of six years. It is interesting to note that the measured bord width for the recently mined section was 6,45 m which means that the actual bord width was extremely close to the design dimension of 6,4 m.

Figure 5.20 shows similar measurements in recently mined and three to four year old continuous miner sections. In the latter section there was no increase in bord width. However, there appears to be an anomaly in the recently mined section. The original surveyor's offsets show a minor population of measurements around 5,6 m which, although this population was observed in the remeasuring of the panel, was not as prominent. A possible explanation could be that the remeasuring concentrated on the centre of the panel, where most load was expected, while the original measurements were taken from all over the panel. As the cutter marks could clearly be seen in the panel on all the pillars, the result should be viewed as a statistical anomaly rather than an actual increase in bord width.

5.5.2.3 Computer analysis of pillar stress

Figure 5.21 shows the stress distribution over the pillars of smallest width and at greatest depth. Assuming that the strength of a unit cube of coal is around 7,2 MPa, stress-induced fractures would not be anticipated in the pillar sides with the geometries of the pillars examined. Therefore, any fracturing in the pillar, or decrease in pillar width, should be a result of blast damage.

5.5.2.4 Pillar condition

Pillar condition in all four panels investigated could be described as very good, even though about 0,25 m of spalling was observed in the panel mined by drill and blast methods six years earlier.

5.6 DISCUSSION AND SUMMARY OF RESULTS

5.6.1 Mode of Fracture Development

Table 5.3 compares, for both collieries, the depth of fractures observed in the recent drill and blast sections to those in the sections mined previously. A remarkable similarity exists between these two sets of fractures.

Table 5.3 Summary of Fracture Observations in Drill and Blast Sections Investigated.

Mine	Panel	Holes with Fractures Observed over Total No. of holes	% Holes with Fractures	Max Fracture Depth (m)	Average Fracture Depth (m)	Increase in Bord Width (m)
Cornelia	Recent	20/40	50	0,23	0,13	-
	3-4 yrs old	25/56	45	0,2	0,1	0,5
Kriel	Recent	20/61	33	0,46	0,27	-
	6 yrs old	25/57	48	0,52	0,17	0,47

At Cornelia Colliery approximately the same percentage of observation holes in the recently mined pillars (50 per cent) showed fractures to the same depth as was found in the pillars mined three to four years previously (45 per cent). However, the older workings showed an increase in bord width of 0,5 m.

The results of the observations at Kriel Colliery showed similar trends. Although the percentage of observation holes with fractures in the recently mined pillars was slightly lower than in the pillars mined six years previously, 33 per cent as compared to 48 per cent, the extent and average fracture depth was similar, despite the 0,47 m increase in bord width experienced over a six year period in the older workings.

The following two questions arise from the results of the fracture observations:

i) why were fractures only recorded in less than 50 per cent of the observation holes, and
ii) why is there a similarity between the results of all panels?

If the mode of spalling was one of continued slabbing of the pillar sidewall, because of high stress concentration, then this, together with an increasing bord width, could be the explanation. However, while this mode of spalling may exist where greater stresses occur because of the depth of the workings, the computer models showed that, at the depth and geometries of mining at both collieries, the stress over the pillar edge was not sufficiently high to cause stress-induced spalling. Another explanation could be that of load on the pillar sides working in combination with the weakened skin of the pillar. But, if this was the case, does spalling continue into the pillar side with time, and does it eventually cease?

The blast-induced cracks appear in a planar rose formation radiating from the blast hole, Figure 5.22, and extend into the pillar side. The cracks may terminate at existing discontinuities or fractures from previous blasts or extend for a distance into the pillar. Fracture intensity is greatest closer to the blast hole. Spalling of the sidewall occurs to a certain distance into the rock and away from the blasthole, Figure 5.22a.

Load on the sidewall induces vertical fractures along this weakened skin of the pillar, Figure 5.22b. A horizontal observation hole will record the vertical fractures at this point. With age, spalling of this layer occurs and the load at the edge of the pillar is transferred towards the pillar centre. As blast-induced fractures extend beyond the slab, Figure 5.22c, further vertical fracturing occurs and this would be recorded in further observations. This process continues as long as the blast-induced fractures extend into the pillar, or until the sidewall segment, although weakened, has sufficient strength to contain the load imposed on it.

This postulation explains the low frequency of fractures found in the observation holes and why slabbing occurs to a similar extent in both the recently and previously mined pillars. It also explains why slabbing continues until an equilibrium is reached. If, however, the reduction of the pillar size is such that the load on the pillar side is great enough to cause stress-induced slabbing, the pillar will ultimately fail. At the depths of the workings under investigation, pillars in older workings should have reached an equilibrium and should, therefore, reflect the full extent of blast-induced damage.

5.6.2 Extent of the Blast Damage Zone

Observations of blast-induced fractures within coal pillars and of the increase in bord width with time showed that the blast damage in the side of a coal pillar extends to a depth of between 0,30 and 0,33 m. The results from Cornelia Colliery showed the extent of the blast damage to be slightly less than that shown in the results from Kriel Colliery.

5.6.3 Benefits of the Continuous Miner

The degree to which mining method affects pillar strength is in the extent or absence of a blast damage zone around the perimeter of the coal pillar. Advantages of the absence of a blast damage zone in a pillar include:

i) increased strength of the pillar, and
ii) greater bord stability.

5.6.3.1 Strength increase of a coal pillar mined by a continuous miner

The safety factor formula is

$$Safety\,factor = \frac{Strength}{Load}, \qquad (5.1)$$

and

$$\sigma_p = \frac{kw^{0.46}}{h^{0.66}}, \qquad (5.2)$$

where σ_p is pillar strength,
k is 7 176 kPa,
w is the designed pillar width (m),
h is the pillar height (m).

As blast-induced damage weakens the side of a drill and blast formed pillar the effective pillar width is

$$w_{effective} = w - 2\Delta w_o. \tag{5.3}$$

Figure 5.23 plots the pillar strength of a continuous miner formed pillar together with the strength of a drill and blast formed pillar with mining heights of 2,0 and 3,5 m over various pillar centre distances. As the pillar size increases, the calculated strength of the drill and blast formed pillar approaches the strength of the continuous miner formed pillar. This shows that the beneficial effect of a continuous miner is greatest with small pillars but reduces with increasing pillar size.

5.6.3.2 Bord stability

While this investigation was primarily concerned with quantifying the extent of blast damage into the pillar side, the effect of blast damage on the immediate strata above the workings is also of concern. Since the roof support installed in drill and blast sections is subject to the dynamic blast wave, the strata are shaken, thereby contributing to loss in roof bolt tension when using mechanical anchors. Conventional techniques will cause the bord width to increase, over a period of time, by about 0,6 m. Bord stability is dependent on the stability of the immediate roof strata and hence the stresses of the roof beam become increasingly critical with increasing span. Since the tensile stresses in the roof are dependent on the thickness of the roof beam as well as on the square of the bord width, Wagner (1980), an increase in bord width from the designed dimensions of 6,0 m to 6,6 m increases the shear stress in the roof beam by 21 per cent. Similarly, an increase from 5,5 m to 6,1 m increases the shear stress by 23 per cent. These stresses become critical in the case of poor roof conditions. The advantage of using a continuous miner is thus enhanced where roof conditions are known to be susceptible to bord failure.

5.6.3.3 Increase in percentage extraction

An obvious benefit of using continuous miners for bord and pillar workings is the reduction in pillar size by the extent of the blast damage zone. Thus a smaller pillar mined by a continuous miner would be equivalent to a conventionally mined pillar after spalling of the blast damage zone has occurred. This assumes that the pillar centre distance, C, is kept constant and the bord width, b, is increased by twice the blast damage zone.

The areal percentage extraction of the drill and blast pillar can be expressed by

$$e\% = e \times 100 = \left(1 - \frac{w^2}{C^2}\right) \times 100, \qquad (5.4)$$

where e is the extraction ratio for conventional blasting,

$$e = 1 - \frac{w^2}{C^2},$$

w is the pillar width,
C is the pillar centre distance.

Reducing the pillar width, w, by the extent of the blast damage zone, $2\Delta w_o$, the extraction ratio of the continuous miner pillar is

$$e_{cm} = 1 - \frac{(w - 2\Delta w_o)^2}{C^2}. \qquad (5.5)$$

The increase in percentage extraction can be expressed in two ways, namely:

the absolute increase in percentage extraction

$$\Delta e_a\% = 100[e_{cm} - e], \qquad (5.6)$$

and the percentage increase in percentage extraction

$$\Delta e_r\% = 100\left[\frac{e_{cm}}{e} - 1\right]. \qquad (5.7)$$