COALTECH 2020

Task 2.5.2

Economic and safe extraction of pillars and associated reserves using underground mining methods

by

Conri Moolman & Ismet Canbulat

September 2003

Executive summary

The project is aimed at identifying and evaluating potential underground mining methods to ensure the economic and safe extraction of coal pillars and associated reserves in the Witbank and Highveld Coalfields.

Through the research it was established that approximately 1.1 billion tons of potentially mineable coal were left underground in the form of coal pillars during the period 1970 to 1997. This number is growing by approximately 110 million tons per annum as a result of the current bord and pillar mining practices. Vast potential exists for the increased utilization of the coal resource through the application of pillar extraction mining methods, especially at greater depth. This holds large economic value as well, despite increased environmental management costs. The development of new and improved pillar extraction mining methods at shallower depth also holds large potential.

The project incorporates a literature survey of previous work done and various site visits with the objective of identifying potentially suitable mining methods as well as limitations, shortcomings and factors constraining these methods. These include environmental impacts, strata control, ventilation, health and safety aspects, etc., both from the history and current mining practices points of view. In addition it includes some international perspectives on high extraction mining methods.

High extraction mining methods are generally used where it has become necessary to extend the life of the mine and are not practiced simply to increase extraction ratios or production. At present, only Tavistock and Tweefontein Collieries are practicing pillar extraction in the Witbank Coalfield, with some Ingwe mines doing partial extraction. Sasol Coal however is practicing various methods of pillar extraction extensively in the Secunda area. Pillars with a nominal safety factor of about 1.8 and higher (using the Salomon and Munro formula) can be successfully extracted.

Extensive site visits highlighted that the operating personnel practising pillar extraction considered discipline and pillar safety factors to be the main areas of concern, more so than the age of the pillars. It was also noted that extracting older pillars was generally more difficult than extracting new pillars.

The primary factors influencing the design and extraction of coal pillars are:

- Pillar conditions

- Roof and floor conditions
- Geological and geotechnical conditions
- Age of pillars
- Surface constraints
- Environmental issues
- Coal quality
- Economic considerations

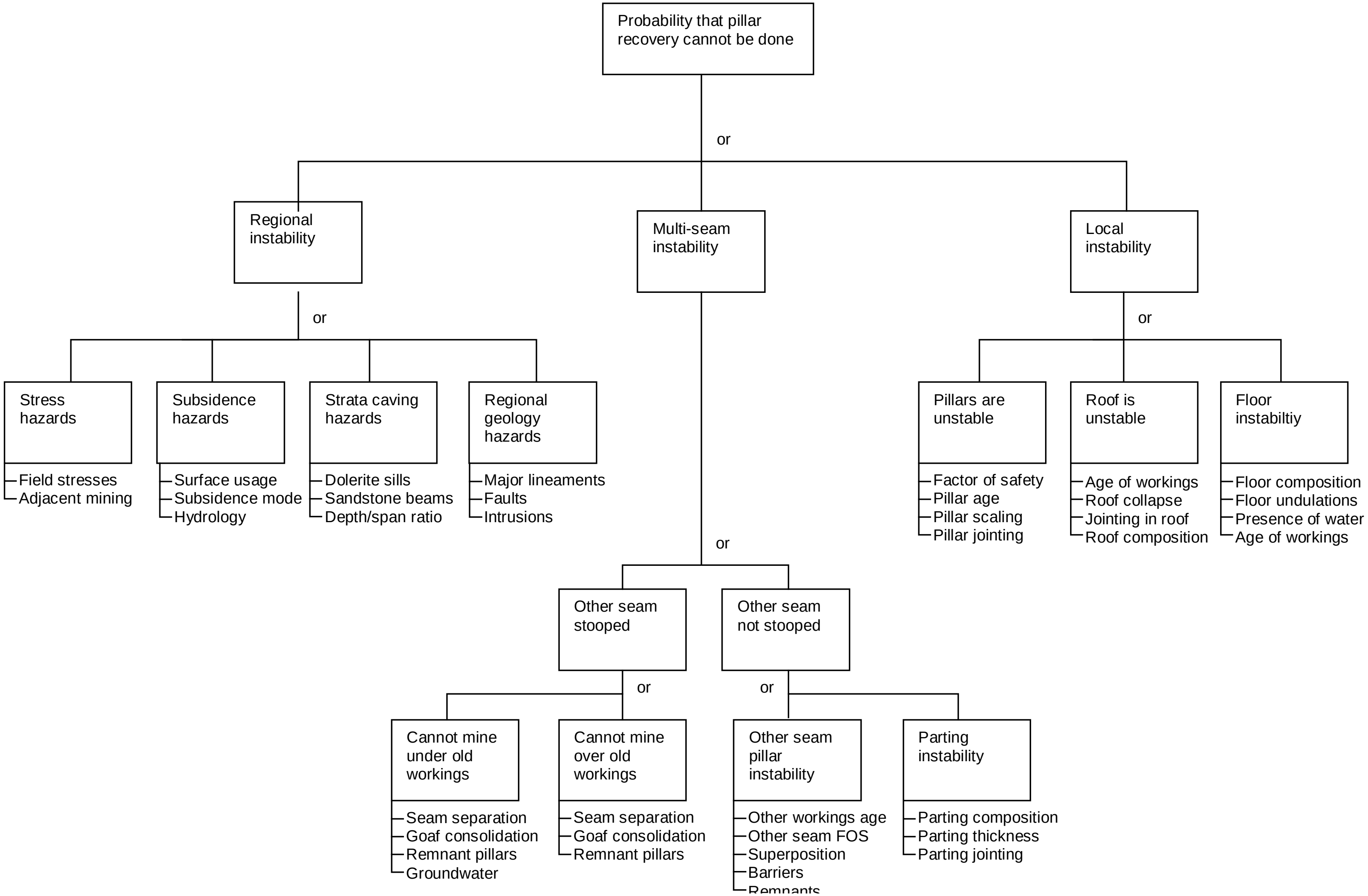
Although it was generally agreed that there is a greater risk associated with pillar-extraction mining than normal bord and pillar development, there was no definite evidence that the fatality and/or injury rate for pillar extraction done with continuous miners is higher than for bord and pillar mining. In fact, it appears that it may even be lower. Furthermore, pillar extraction is considered safe up to heights of 3.5 m, after which pillar splitting, robbing or partial pillar-extraction methods are used.

Nevid pillar extraction method has been identified as one of the potential methods to be used in pillar extraction. However, this method has usually been applied at greater depths (>150 m) by Sasol. As part of this study a detailed investigation of the application of Nevid method at shallow depths was conducted. The dimensions of the cutting widths and snook sizes were established.

The study into the effect of panel widths showed that the panel width is one of the most important parameters in determining the load and the safety factors of pillar in the active mining zone. It is suggested that the panel widths should be reduced in order to reduce the load acting on the pillars.

In addition, abutment angle, which also determines the load acting on the pillars in the active mining zone, was found to be an important parameter in pillar extraction. Detailed calculations of the safety factors and the load acting on the pillars in the active mining zones were presented.

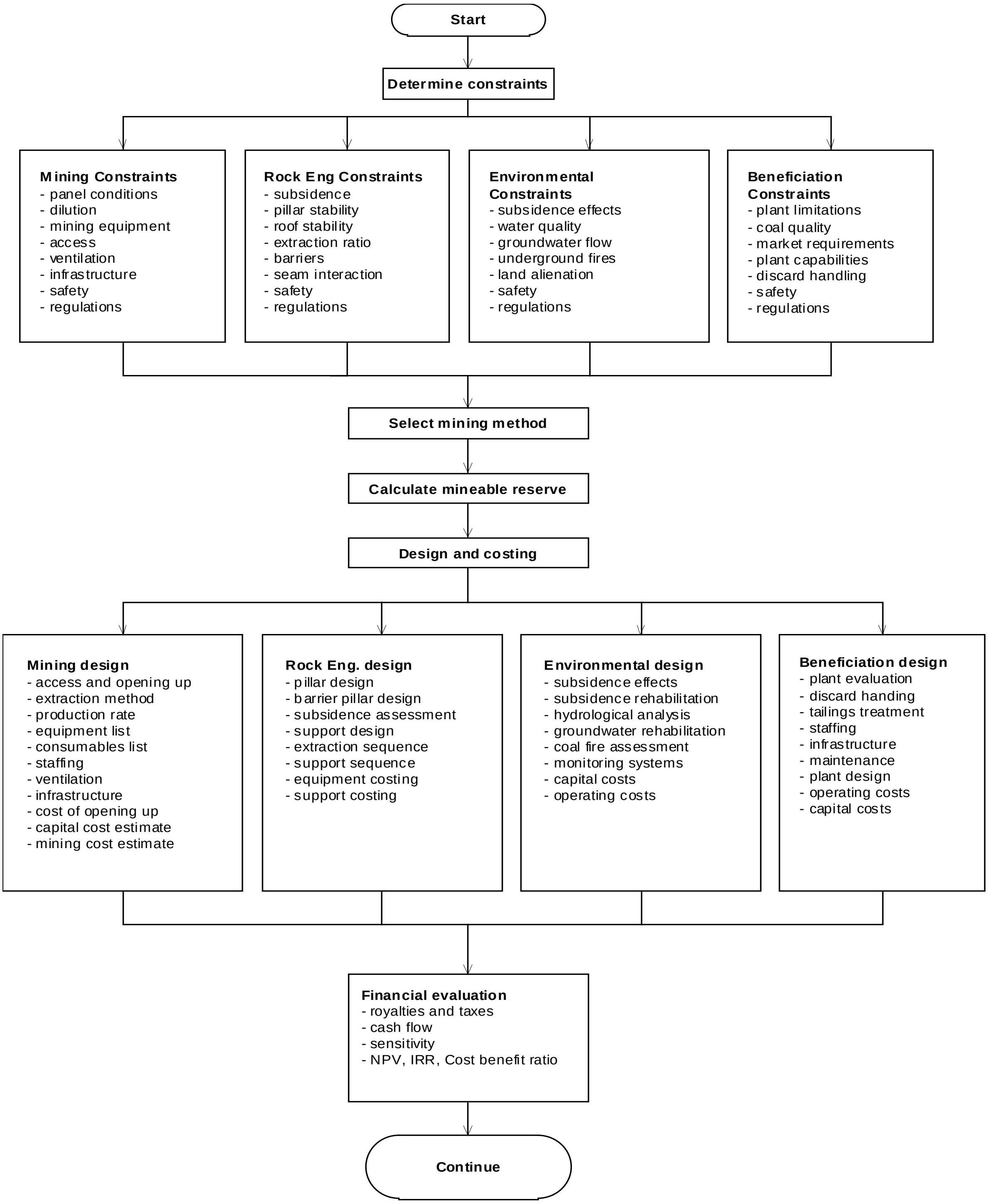
Five design flow sheets for rock engineering, environment assessment, mining, coal beneficiation, and financial evaluation have been developed for the decision making process. However, because so many parameters used in different flow sheets, the design flow sheets were rationalized into simple flow sheets for decision making process in pillar extraction.



Fault tree for stability risk evaluation

The project proposes a rock engineering risk rating system to evaluate all potential pillar extraction panels for possible selection as future pillar extraction panels on a pre-feasibility level (see page Figure overleaf).

This pre-feasibility study was incorporated into a spreadsheet and available to COALTECH 2020 participants. This is then followed by a full feasibility study for final selection (below Figure).

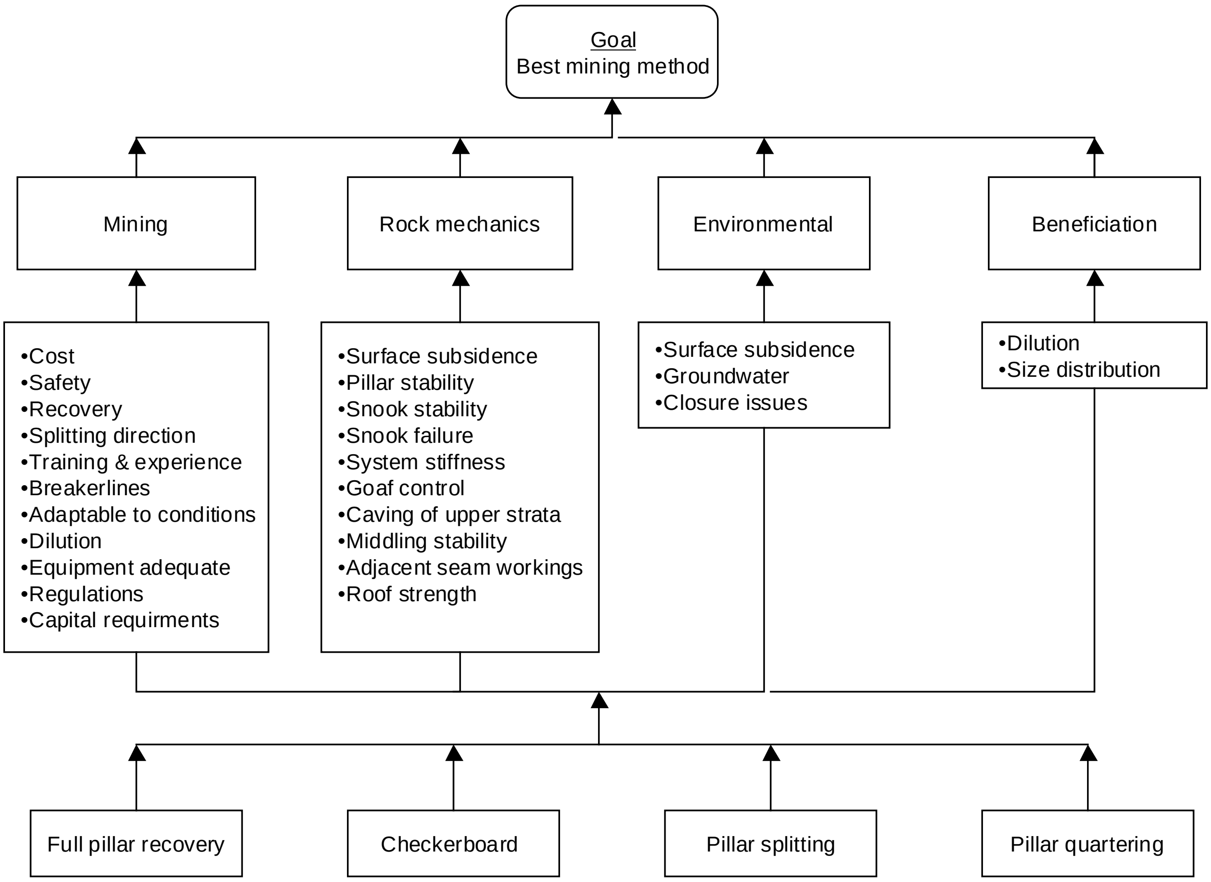


Flowchart for feasibility study

Four basic approaches to the utilisation of coal left behind in pillars are proposed in the final selection of the most suitable mining method. The selected potential pillar extraction panels are finally evaluated in a decision support system based on the Analytical Hierarchy Process to select the most suitable mining approach. Various detailed mining methods are included in the report for the selection of a specific method or to form the basis for the development of a new method.

The outline of the AHP process may be summarized as shown below. The goal of finding the best method is set. Below the goal, the criteria are subdivided into disciplines. The relative weighting of each criterion is determined using pairwise comparisons. Finally the alternative methods are evaluated, using pairwise comparisons against each of the criteria. The outcomes are manipulated mathematically to provide the best solution.

The method has been programmed into a spreadsheet, so that users do not need to carry out the calculations themselves. The spreadsheet program is specifically designed to evaluate the problem of mining method selection, using the criteria listed above.



Outline of analytical hierarchy process for selecting best method

From the literature survey and the workshops held, serious shortcomings in the mining methods currently available and their applicability for the mining of thin seams (less than 1.5 m) were identified. This area has however been targeted for future research and the report will primarily focus on the medium to high seam range.

In conclusions it is strongly recommended that the methods and guidelines given in this project should be applied in an actual pillar extraction project in order to determine the applicability of them.

Project team members

The project team members responsible for the project are as follows:

Gavin Lind, University of the Witwatersrand
P van Vuuren – University of Pretoria
Prof. H R Phillips, University of the Witwatersrand
D Hardman, University of the Witwatersrand
Dr N van der Merwe, CSIR Division of Mining Technology
G S Esterhuizen, Steffen, Robertson and Kirsten, USA

Table of contents

List of Figures

List of Tables

Introduction

1.1 Importance of secondary extraction

The aim of Coaltech 2020 is to extend the life of the Witbank coalfield beyond 2020. Large areas of this coalfield have previously been mined using the bord and pillar extraction method, leaving significant amounts of coal in the pillars. However, the constraints on secondary pillar extraction imposed by geotechnical, rock engineering, environmental and economic factors may have an adverse effect on their potential for being mined.

South Africa is considered to have between 55 and 58 billion tons of coal reserves, of which approximately 29 per cent are found in the Witbank and Highveld Coalfields (Jeffrey, 2000).

South Africa is currently the second-largest exporter of hard coal in the world. In 1998, 60.5 million tonnes of steam coal, 5.7 million tonnes of metallurgical coal and 1.3 million tons of anthracite were exported (Jeffrey, 2000).

Baxter (1998) investigated the total coal production of South Africa for the period 1996 to 1997. He concluded that the South African coal mining industry produced 109 million tonnes of coal (ROM) from underground bord-and-pillar workings in 1997.

Madden *et al*. (1995) investigated the dimensions of underground bord-and-pillar workings for more than 350 panels in South Africa (refer to Figure 0–1). The average dimensions were given as:

Bord width : 6.0 m
Mining height : 2.8 m
Pillar width : 15 m
Depth : 101 m
Safety factor : 2.82.

From these figures the number of pillars left underground in 1997 can be calculated as follows:

1. Volume of one pillar : 630 m^3

2. Total volume of mined area (one pillar) : 1 234.8 m^3
3. Extracted volume : 604.8 m^3
4. Weight of extracted volume : 967.7 tonnes
5. Total pillars left u/g in 1997 : **112 641**
6. Total volume of pillars left u/g : 70.9 million m^3
7. Amount of coal left u/g in 1997 : **113.5 million tonnes.**

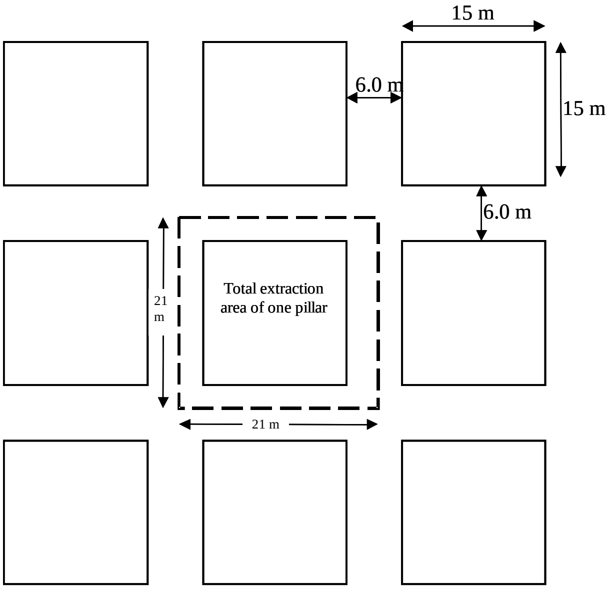


Figure 0–1 Average dimensions of underground bord-and-pillar workings in South African collieries (after Madden et al., 1995)

The above figures indicate that the average underground extraction ratio was just less than 50 per cent.

Assuming that the average bord-and-pillar coal production ratio has been 35 per cent of the annual ROM production since 1970, the above figures can be extended using the production figures obtained from the Department of Minerals and Energy (Figure 0–2).

From Figure 0–2 it can be calculated that:

- For the period 1970 to 1997, **1.68 billion tonnes of coal was left underground**
- **More than 1.7 million coal pillars** have been left underground since 1970
- This covers an area of **27 x 27 km (729 km^2)**
- Sufficient coal is left in the pillars to sustain ROM production for 17 years, excluding barrier pillars.

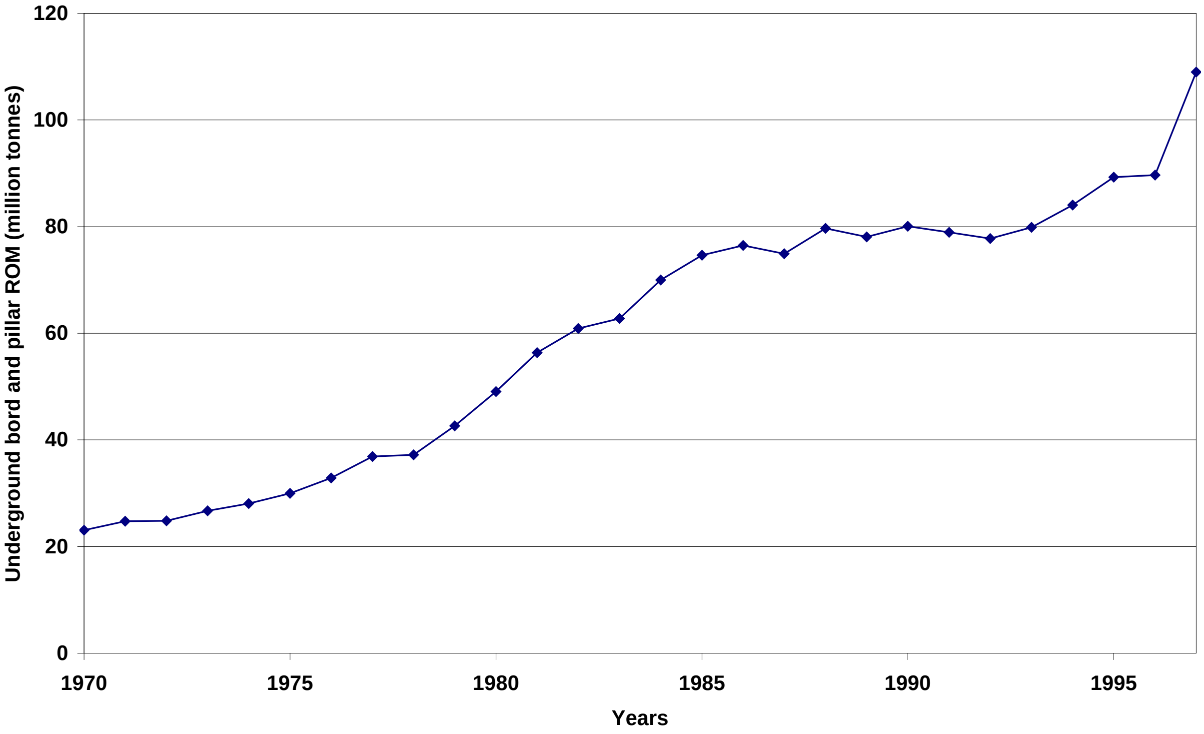


Figure 0–2 Estimated underground bord-and-pillar coal production for the period 1970 to 1999

Note that these figures are based on the assumption that the bord-and-pillar production rate has remained at 35 per cent of the total production since 1970. However, in the earlier years this figure was probably higher. Moreover, Baxter (1998) separated underground primary production and pillar-extraction figures in his paper. This indicates that none of these pillars will be extracted, i.e. 109 million tonnes of coal is produced only from primary bord-and-pillar mining. In other words the production of 109 million tonnes of coal is excludes the production that came from pillar extraction.

In another study, Hardman (1989) estimated that 1.7 billion tonnes of coal in 4 million pillars over an area measuring 32 x 32 km remains as a consequence of bord-and-pillar mining in South Africa.

1.2 Increased extraction

In order to obtain the potential increase in reserve utilisation, a comparison was drawn between the theoretical percentage extraction for a number of different mining approaches at varying depth. The following different mining approaches were evaluated in terms of impact on percentage extraction of coal and life of the reserve area: -

- Normal bord and pillar mining at a safety factor of 1.6 as per Salamon formula.
- Bord and pillar mining at a safety factor of 1.6 as per Salamon formula, but adjusted for continuous miner application.
- Bord and pillar mining at a safety factor of 1.2 as per Salamon formula with subsequent ashfilling.
- Bord and pillar mining followed by pillar splitting.
- Bord and pillar mining followed by pillar splitting and quartering.
- “Full pillar extraction” as applied at Middelbult.
- The Nevid method of pillar extraction.
- Bord and pillar mining at a safety factor of 1.6 as per van der Merwe (2000) formula.

A number of very general and broad assumptions had to be made to simplify calculations and relative comparison of the results.

- In all cases panels were restricted to 7-road layouts.
- Solid barrier pillars were left around all panels.
- The coal left in the barrier pillars formed part of the calculation.
- A minimum width to height ratio of 2.5 was used in pillar design.
- A minimum initial safety factor of 2.0 is required for pillar extraction.
- A minimum pillar size of 18 m is required for effective splitting in the so-called full pillar extraction as applied at Middelbult Colliery and the Nevid method of pillar extraction.
- The final ribs after splitting in pillar splitting must have a width of at least the mining height.
- The remaining pillars after splitting and quartering in pillar splitting and quartering must have a width of at least 1.3 the mining height.
- In pillar splitting and quartering, a full row of pillars is left on one side of the panel to provide for a bleeder road.
- In “full” pillar extraction, a full row of pillars is left on either side of the panel to provide for a bleeder road.
- In the Nevid method, a full row of pillars is left on the one side of the panel and two-thirds of a row on the other side to allow for a bleeder road.
- In “full” pillar extraction only 60 per cent of the coal in each pillar is recovered due to spillage and inconsistent cutting. This is based on practical experience at Sasol Coal.

- In the Nevid method, the percentage extraction is calculated theoretically based on the cutting layout as a result of less spillage and easier adherence to the layout.

In all cases the overall percentage extraction can be increased somewhat by mining the barrier pillar between adjacent panels creating larger compartments. Extracting the barrier pillar and the solid pillars left on one side of a panel during secondary mining and leaving only a bleeder road around the outer reaches of larger compartments can significantly increase overall extraction.

Increasing the number of roads also improves the overall percentage extraction in all cases, but at greater pillar sizes, productivity suffers and shuttlecar cable length may become a limiting factor. At shallower depths and smaller pillar centres this should become a serious consideration.

It must further be borne in mind that with all high extraction methods at shallow mining depth predictability and consistency of goafing may become a major problem. Severe surface subsidence and damage further aggravate the problems. The methods discussed in this document definitely require further investigation for shallower depths.

Figure 0–3 presents the results for the percentage extraction for the various mining methods at depths ranging from 50 m to 175 m.

For both pillar extraction and the Nevid method, the percentage extraction remains constant up to approximately 150 m. This is a result of the minimum pillar size requirement set by the mines from a practical cutting layout. For the splitting and splitting and quartering alternatives, a similar correlation is found at the shallower depths. This is a result of the overriding requirement of width to height ratios for the final ribs or pillars.

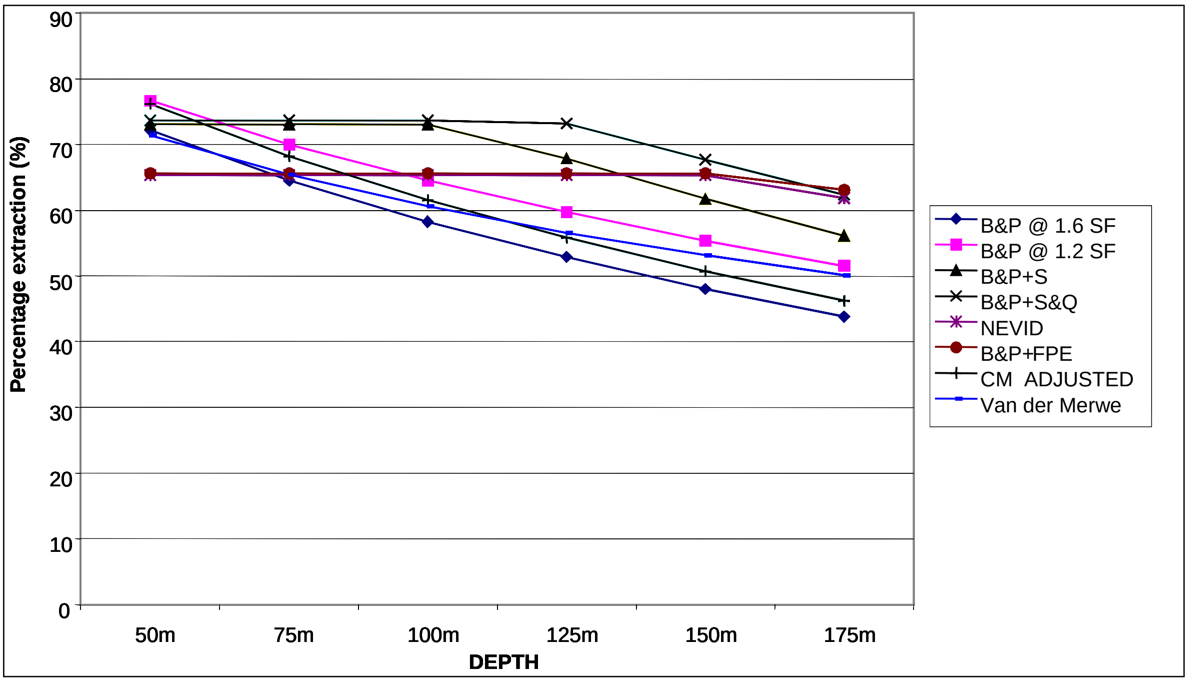


Figure 0–3 Percentage extraction ratios for various mining methods

As can be seen from this Figure that the various bord and pillar alternatives are doing better than the pillar extraction alternatives at shallow depths. This is primarily as a result of the selected minimum pillar requirements for the pillar extraction methods. There are currently mines practicing pillar extraction on smaller pillars with different cutting layouts and sequences with good results. The continuous miner adjusted safety factor of 1.6 and the low safety factor of 1.2 based on the Salamon formula gives similar results for mining at very shallow depth. Both splitting and splitting-and-quartering of pillars up to approximately 150 m depth and the pillar extraction alternatives at shallower depths up to approximately 80 m may result in unstable mining conditions and should be approached with great care. As the safety factor is some reflection of the ability of the remaining coal to carry the load of the overburden, it can be deduced that the higher the percentage extraction, the greater the possibility that the remaining coal pillars or snook will fail. The critical issue is the safe time to failure, which becomes very unpredictable with inconsistent snooks dimensions and small pillars at shallow depth. Splitting and splitting and quartering of pillars to achieve the indicated percentage extraction above may be far too risky especially in the 75 m to 125 m depth range and should rather not be considered. One of the other methods should be employed in these situations.

From approximately 80 m, pillar extraction appears to be the best alternative from a reserve utilization point of view, followed by mining at a safety factor of 1.2 with subsequent ashfilling. During low safety factor mining, the stability of the area together with the risk of pillar failure whilst mining and ashfilling is still in process as part of Coaltech 2020. The continuous miner adjusted safety factor of 1.6 at shallow mining, however approaches the unadjusted 1.2 safety factor in terms of percentage extraction and pillar sizes, indicating similar risk. The same is true for mining at a 1.6 safety factor according to van der Merwe (2001) at the greater depth of 150 to 175 m. If the continuous miner adjustment and the van der Merwe strength formulae are acceptable, mining at a 1.2 Salamon and Munro (1967) safety factor would almost not require ashfilling.

In general, it can be concluded that from a reserve utilization point of view, bord and pillar mining only should be recommended for mining at depths up to approximately 80 m, except if alternative pillar extraction methods or layouts can be developed. From 80 m onwards some form of pillar extraction should be implemented. Although splitting and splitting and quartering appear attractive in the middle depth ranges, the risk associated with these approaches may be unacceptable.

1.3 Financial value of increased extraction

1.3.1 Production scenario’s

A hypothetical reserve area of 154 Mt in-situ mineable coal of 3 m thickness was theoretically mined to depletion at a constant rate of 4.5 Mtpa with 5 different mining approaches. This was repeated for depths varying from 50 m to 175 m in order to assess the impact of depth on the percentage extraction and the resultant economy of the approach. Similar mining layouts were used in all cases to ensure maximum consistency in the comparisons. The basis for the financial evaluation and comparison was the NPV (net present value) of the cash flow generated over a period of 27 years. This is the maximum mine life that could be generated in the exercise. The impact of water treatment associated with pillar extraction was considered only up to year 27 in all cases as discounting of numbers beyond that timeframe is very insignificant. It should be noted though that water treatment will most probably carry on well beyond that date.

The 5 mining approaches evaluated were :-

- Bord and pillar mining at a 1.6 safety factor.
- Bord and pillar mining at a 1.6 safety factor adjusted for continuous miner application.
- Bord and pillar mining at a 1.2 safety factor, followed by ashfilling.

- Bord and pillar mining at a 1.2 safety factor adjusted for continuous miner application, followed by ashfilling.
- The Nevid method of pillar extraction.

In the ashfilling approach, the area was backfilled with a cemented ash to approximately one third of the original mining height, resulting in a residual safety factor of 1.6 based on the assumption that the backfill will have the same strength as the coal. Although, this is not true in reality, it was though this aspect requires a very detailed research, and it is not the scope of this project.

Capital required to establish a new mine with a 4.5 Mtpa production capacity was estimated at R638 million and a multi stage washing plant with stockpiles and rapid load-out facilities including railway links at R730 million. In the base model it was assumed the export yield would amount to 35 per cent and middlings yield to 50 per cent. Cash operating cost for mining was estimated at R45.5 per RoM tonne for bord and pillar development and R43 for pillar extraction. The difference is primarily related to lower coal cutting and roof support costs.

1.3.2 Pillar extraction and ground water inflow

During pillar extraction, the goaf migrates through the overlying strata into the groundwater aquifer in almost all cases, resulting in an inflow of groundwater into the mine workings. Over time, the volume of water reporting underground is largely a function of the rainfall. It is estimated that on average 8 per cent of the mean annual rainfall recharges the groundwater system and ends up underground in the mine. This figure is however dependant on a number of variables and could range from a low 3 per cent to a high 15 per cent. Rainfall also varies significantly from year to year. In the base model a recharge rate of 8 per cent and an average rainfall of 750 mm per annum were used.

In the underground workings, the water is contaminated through chemical and biological processes in the presence of various minerals. The longer this process, the worse the resulting water quality. In the model, it is assumed that water is pumped to surface and treated as soon as possible, which should result in lower overall treatment costs. Water treatment plants are built in increments of 1 Ml per day capacity following the profile of increasing groundwater inflow. The model uses a capital estimate of R20 million per 1 Ml per day capacity as baseline. Comparison of actual figures in industry is currently as high as approximately R40 million, and operating cost of R6000 per 1 Ml treated. Lower cost alternatives are in the process of development and better water management will result in better water quality and lower costs.

1.3.3 Low safety factor mining followed by ashfilling.

In this case the reserve is mined at a safety factor of 1.2 adjusted for continuous miners. This results in the smallest pillar sizes and highest percentage extraction for any given safety factor and mining situation, but also results in the weakest pillar strength and most unstable mining condition at any given safety factor as discussed in Section 3. This poses the highest risk during mining and subsequent ash filling and the potential time to failure of pillars may force alternative mine layouts to reduce panel length and time of exposure. Failure of pillars before solidification of the ash may result in failure of overburden and flooding of adjacent workings with water and ash.

With a cemented ashfilling of final strength equivalent to the strength of coal (assumption), the mined out area must be back filled with ash to reduce pillar height to two thirds of the original mining height to increase the residual safety factor to 1.6. This implies filling at least one third of the mined out volume with ash, which would require 1,000,000 cubic meters of filling material per annum.

Capital provided for backfill infrastructure in the base case in the model amounts to R35 million, with operating cost of R10 per cubic meter placed.

1.3.4 Financial evaluation.

Table 0–1 shows the financial parameters that were used in the modeling.

Modeling the above scenario produced the following result at various mining depths: -
(insert NPV @STD COST)

From the above comparison it appears that pillar extraction only becomes viable beyond approximately 150 m given the current assumptions when compared to bord and pillar mining at a safety factor of 1.6 adjusted for continuous miners. Furthermore mining at a safety factor of 1.2 is only more viable than pillar extraction at depths of approximately 75 m and shallower, and will only surpass bord and pillar mining at a safety factor of 1.6 much deeper than 175 m.

Given the basic assumptions, bord and pillar mining at a safety factor of 1.6 adjusted for continuous miners appears to be the best option up to depths of approximately 165 m.

Table 0–1 Financial parameters used in the model

Element	**Value**
Export price	$29
Middlings price	R65
R/$ Exchange rate	R9.5
Export price increase per annum	2%
Middlings price increase per annum	5.8%
R/$ increase per annum	3.8%
Cost increase per annum	8%
Capital increase per annum	8%

It must however be stressed that the NPV method of financial evaluation does not necessarily reflect the true value of a diminishing resource such as coal and that the time value of money further distorts the picture. The picture is further distorted by the limitations placed on the Nevid mining method based on current experience. Adjusting cutting widths during pillar extraction may result in smaller pillars being extracted at higher percentages as used in the model.

1.4 Conclusion

Given the current assumptions, its appears that the application of pillar extraction is significantly smaller than what was previously believed. This is however caused by the specific assumptions used. Improvement in the percentage extraction with adjustments made to the Nevid method for shallower depths will dramatically improve the situation. Extracting the barrier pillar between adjacent panels together with the adjacent pillars left to create the bleeder road will also make a significant difference as is the case at some existing operations. Carrying the water treatment cost well beyond the life of the mine will worsen the situation. With this in mind, and the fact that we are utilizing a diminishing resource which should be exploited to its full, tremendous effort should be put into water management to improve water quality. This should be backed by an even more dedicated research effort in finding more economic water treatment technologies, both from a capital and operating cost point of view.

Considering ashfilling, it should be realized that given the requirement of strength and stabilizing properties, it is highly unlikely that suitable ash mixtures can be developed within the cost framework. In addition, the determination of suitable strength of ashfill requires a detailed research project.

Research methodology

The research commenced with a literature survey to review previous work done on the subject of increased extraction of coal reserves. This covered both the local and international coal mining experience. The objective of the literature survey was to establish the current level of knowledge and to identify the constraints of current mining methods in terms of pillar extraction, as well as to identify possible methods for future application in the research. This led to the compilation of a questionnaire to be used as a base for structured visits to selected pillar extraction operations.

The literature survey was followed with visits to various pillar extraction operations in South Africa and in Australia to gain first hand knowledge of the South African and Australian pillar extraction experience. The objective was again to further identify factors constraining and limiting pillar extraction applications and possible methods to include in the research. These were aimed at issues such as the environment, strata control, roof and floor stability, ventilation, mining methods and health and safety implications. The interrelationship of these factors was required for the development of various risk assessment and evaluation models.

The site visits and literature survey were followed by industry workshops in which feedback was given to a number of selected industry role players with the objective to develop further interaction with the industry and to brainstorm and discuss existing and possible new mining methods for future application.

A number of models were then developed for use in the evaluation and selection of possible methods for future pillar extraction operations. The theoretical percentage extraction of various approaches to high extraction mining methods was compared over varying mining depths below surface. The potential economic benefit of increased extraction against the additional cost of environmental protection/remediation was modelled. The various factors identified that constrain and limit the application of pillar extraction were subsequently built into models for doing risk assessments relating to mining and rock engineering. The research was concluded with a model that assists in the selection of the most appropriate mining approach for any given panel

Literature survey

1.5 Introduction

It has been established that an increase in the utilisation of South Africa's coal resources is needed, both to sustain this industry and to ensure that offshore revenue from exports is maintained. Previous extraction of the coal reserves has been done predominantly by the bord-and-pillar method of mining, with percentage extraction by this method (by means of primary and secondary extraction of pillars) accounting for approximately 50 per cent. This implies that almost half of the extractable coal reserves in the Witbank and Highveld coalfields remain to be unexploited. Considering that coal mining has taken place in this region for more than a century, a sizeable volume of coal is obviously still available for economic exploitation.

This literature review identifies and discusses the factors associated with the removal of previously developed coal seams, i.e. pillar extraction. These factors include the mining methods, the coal pillars, and the safety aspects related to this mining practice.

1.6 Mining methods

Longwall mining has been practised successfully in South Africa since the late 1970s. However, due to the presence of geological anomalies and the varying thickness of the coal seams, it can only be practised in selected portions of the total reserves (Beukes, 1989). The other, more dominant, mining method employed since the inception of coal mining in South Africa is bord and pillar. The percentage of coal lost as a result of larger pillars being left in bord-and-pillar workings the deeper one goes was a major factor identified by Wagner (1981) as indicating the need to increase the total percentage extraction of coal reserves. It therefore became necessary to investigate other mining methods for improving the overall extraction percentage of the total coal reserves.

Pillar extraction (or stooping) has been practised for many years in South African collieries as a means of increasing the percentage extraction from the in situ coal reserves. Optimised recovery is the main objective in pillar extraction. Early efforts with this mining method in the Witbank area were not as successful as in the deeper, thin seams of Natal (Salamon and Oravecz, 1973). Handgot methods (hand lashing with spades) of pillar extraction have been replaced mainly by mechanised methods, using either conventional mechanised equipment or, more commonly, continuous miners. As a means of increasing the percentage extraction, pillar extraction has certain advantages over the highly mechanised longwall method, which will be discussed later. Mark and Chase (1999) describe a computer program (called Analysis of Retreat Mining Pillar Stability, or ARMPS) that is used as an aid in the design of pillar extraction operations. This and other design tools are further discussed in the section on Design of Suitable Areas (Sub-section 1.9.3.8).

1.6.1 Decision-making considerations for pillar extraction

Plaistowe *et al.* (1989) suggest that consideration should be given to optimising extraction on the basis of coal qualities and not on a purely volumetric extraction basis. They further develop a logic sheet to ensure that every possibility or opportunity has been identified. From this, areas are identified from which higher extraction would be obtained by pillar extraction and those from which higher extraction would be obtained by bord-and-pillar mining. This analysis does not take into account losses from geological disturbances. Livingstone-Blevins and Watson (1982) state that it must be ensured that pillar extraction is the most appropriate method to the prevailing circumstances.

Plaistowe *et al.* (1989) suggest further criteria for decision-making about pillar extraction, highlighting the mining method, speed of extraction, ventilation and choice of equipment as important factors. Livingstone-Blevins and Watson (1982) suggest similar decision-making criteria.

Wagner (1981) suggests that compared with longwall mining, pillar extraction methods offer the advantages of lower capital cost and greater flexibility with regard to geological disturbances. He further comments that pillar extraction methods not only have the potential to supplement longwall mining but also in many instances could replace this total extraction method. Furthermore, he mentions that compared with longwall mining, the pillar extraction method makes maximum use of the load-bearing capabilities of coal, thereby avoiding the need for powerful artificial supports, which are the main feature of the longwall mining system. Blaiklock (1992) adds that pillar extraction is often employed in deeper, high-value seams where recovery rates would be unacceptably low if only development bord-and-pillar mining was conducted.

1.6.2 Planning for pillar extraction

It is clear from the introduction that bord-and-pillar mining has been, is and, for the foreseeable future, will remain the primary underground mining method for coal extraction in South Africa. Livingstone-Blevins and Watson (1982) and Willis and Hardman (1997) maintain that pillar-extraction mining can come from only two sources: old pillar workings or virgin coal. It follows that in old workings, planning can only optimise the given circumstances (in terms of the original safety factor, the prevailing geological and other conditions, etc.), whereas in virgin coal, planning can play a more effective role. Most coal seams in South Africa have been mined by the bord-and-pillar method and the historical panel designs did not cater for secondary extraction of pillars by pillar-extraction mining.

Livingstone-Blevins and Watson (1982) make further mention of the importance of the panel system (with its associated barrier pillars) in coal mine design. The major advantage of this system is that the extent of fire or pillar collapse can be confined. Other advantages are that pillar extraction can commence before primary mining has been completed and that panels can be designed specifically for ventilation. Panel design came into favour only after recommendations made by Salamon and Munro in 1967, in which they indicated that a large proportion of bord-and-pillar workings were not designed in panels (Salamon and Munro, 1967). Livingstone-Blevins and Watson (1982) further suggested that panel design is limited by the area available, and could be limited by geological conditions or surface boundaries.

Pillar extraction can be conducted in two ways, namely advance or retreat. Retreat pillar extraction is conducted on completion of primary mining, whereas advance pillar extraction is conducted simultaneously with primary mining. This report concerns itself with the pillar extraction of existing bord-and-pillar workings, with the emphasis being on the retreat method of pillar extraction.

Stooping practice in South Africa can be divided into two basic methods: pillar extraction and rib pillar extraction. Beukes (1989) highlights the difference between the methods:

> *“Pillar extraction – the panels consist of a bord-and-pillar mining layout where many pillars are created but only extracted at some later date as a panel must be developed completely before pillar extraction can commence. There are two basic approaches to pillar extraction. Firstly, the extraction of pillars in old workings where little or no account was taken of secondary extraction during the initial panel and pillar design, and secondly, the extraction of pillars in panels designed specifically for pillar extraction.*

> *"Rib pillar extraction – the panels are created by means of primary development consisting of three to four roads. Secondary development is then used to cut the panel into 42 to 72-m wide ribs. Rib pillars, normally referred to as fenders, are then developed and extracted very soon after creation. The only exception is the pillars created by the primary and secondary development which are extracted as the section retreats."*

Wagner (1981) makes the following comments on the basic principles of pillar extraction:

> *"All pillar-extraction methods have in common that the extraction panels in the primary mining phase pillars are developed which are then extracted in the second phase of the operation. The main objective of the pillars is that they should provide support of roof strata during the primary and secondary mining stages thereby protecting men and equipment against roof falls and regional collapses. However, as the supporting pillars are reduced in size during the actual pillar-extraction phase, they lose the ability to support the weight of the overburden. Pillar-extraction layout must therefore be designed in such a manner that the support of the superincumbent strata during the extraction of an individual pillar or number of pillars is taken over by neighbouring pillars. The support role of the coal during the extraction of a pillar is reduced to that of providing support to the immediate roof strata. In the final stages of extraction of a pillar, this support is removed as well and the temporary support of the exposed roof which relies entirely on roof bolts and sticks that were installed during the primary and secondary phases of mining. Once the pillar has been extracted and men and equipment have been withdrawn, the temporary support that is mostly in the form of sticks is removed to encourage the roof strata to cave. This latter part of pillar extraction is an integral part of the pillar-extraction method and failure of the strata to cave in the mined-out area can jeopardise the success of this mining method."*

1.6.3 History of pillar extraction

The method of pillar extraction offers the possibility of a high degree of recovery of reserves. This method of mining practised widely with success in the thin and relatively deep-lying coal seams of KwaZulu-Natal. Early efforts at pillar extraction in the thicker and often shallower coal seams in the Witbank area did not meet with similar success. These operations often resulted in mine fires by spontaneous combustion as a result of the large amount of broken coal left behind.

Pillar extraction is not practised widely in European collieries, partly because the coal seams are located at comparatively great depths (300 m or more below surface), which has encouraged the use of longwall techniques that are inherently safer. Australia, the USA and South Africa delayed the use of longwall mining due to its high capital cost and because their coal seams are at shallower depths (generally less than 300 m). A further point is that longwall mining demands comparatively undisturbed coal seams to be cost-effective.

The first experiments with rib-pillar mining in South Africa were modelled on the methods that were successfully used in New South Wales, Australia. These methods, namely Munmorrah, Wongawilli and Old Ben, are all rib pillar-extraction methods using continuous miners. Each of these methods (as originally employed) is briefly discussed below (Beukes, 1989).

1.7 International experience

1.7.1 The Wongawilli system

A panel is created by a secondary development consisting of three to five roads, leaving a continuous pillar of coal between the development and the previously caved area. This pillar of coal is normally between 50 and 150 m wide and is extracted by developing and extracting 7-m-wide ribs in a modified split-and-lift system. The pillars formed by the development are extracted as the rib extraction retreats. As a result of the length of the rib pillars, this method resembles a shortwall face. A typical Wongawilli layout is shown in Figure 0–1.

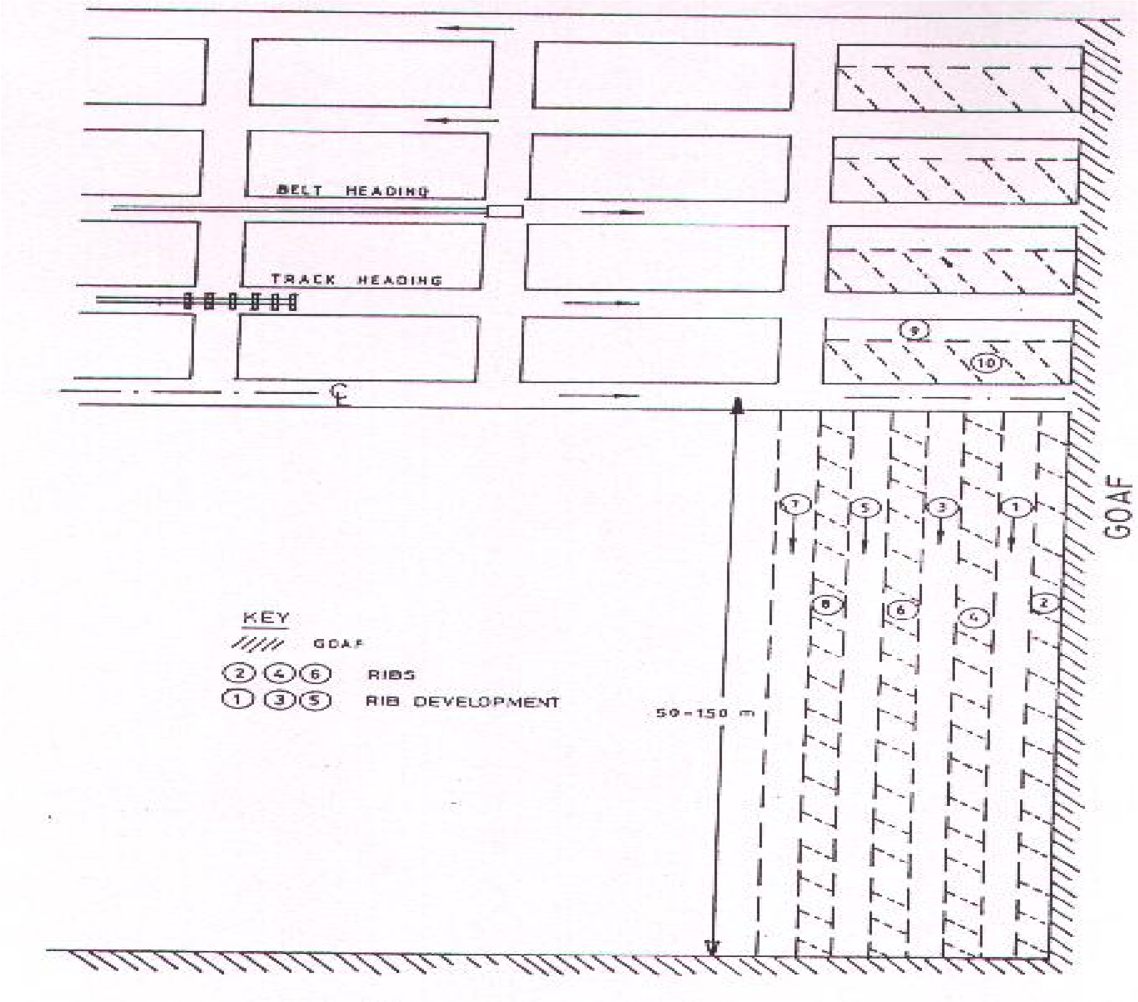


Figure 0–1 Typical plan view of the Wongawilli system (after Skybey, 1982)

The main disadvantages of the system are:

- Excessive floor lift when splitting successive headings in a large panel
- Difficulties when removing snooks on the return run out of each heading
- Difficulties with ventilating rib-pillar panels when the roof caves completely, filling all voids in the goaf area.

1.7.2 The Munmorrah system

The Munmorrah system is practised at an average depth of 180 m below the surface. The coal seam is on average between 1.8 and 3.0 m thick and is hard, making it difficult to cut with a continuous miner. The floor is composed of soft shales and floor heave often occurs due to pillars being forced into the soft floor. The rib pillars are normally 1 200 m long and 183 m wide, and are developed on either side of the main development. The primary development consists of three roads, with the bord width being 5.5 m and the pillar sizes 26 m x 40 m centres. Figure 0–2 shows a typical extraction sequence and layout of this mining system.

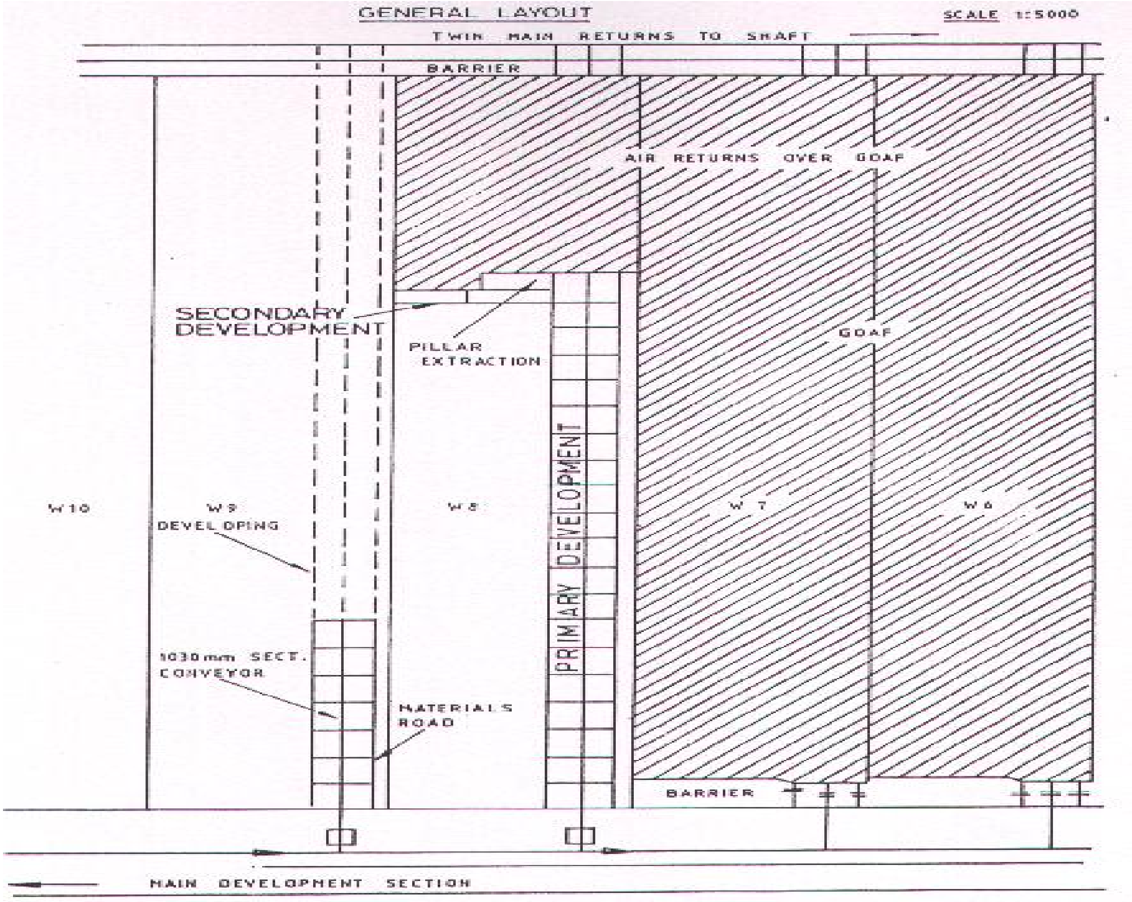


Figure 0–2 The Munmorrah mining system (after Beukes, 1989)

1.7.3 The Old Ben method

This method is very similar to the Munmorrah method and was developed after a very serious accident occurred in which the very thick, competent conglomerate overlying the coal seams caused sudden, unplanned roof falls. Here, the secondary development consists of three roads, leaving reserves for pillar extraction on either side. The total panel width is more than 200 m. Tertiary development, consisting of three roads, is done towards the end of the panel. From this development, short fenders are then developed and extracted. A typical layout of this method is shown in Figure 0–3.

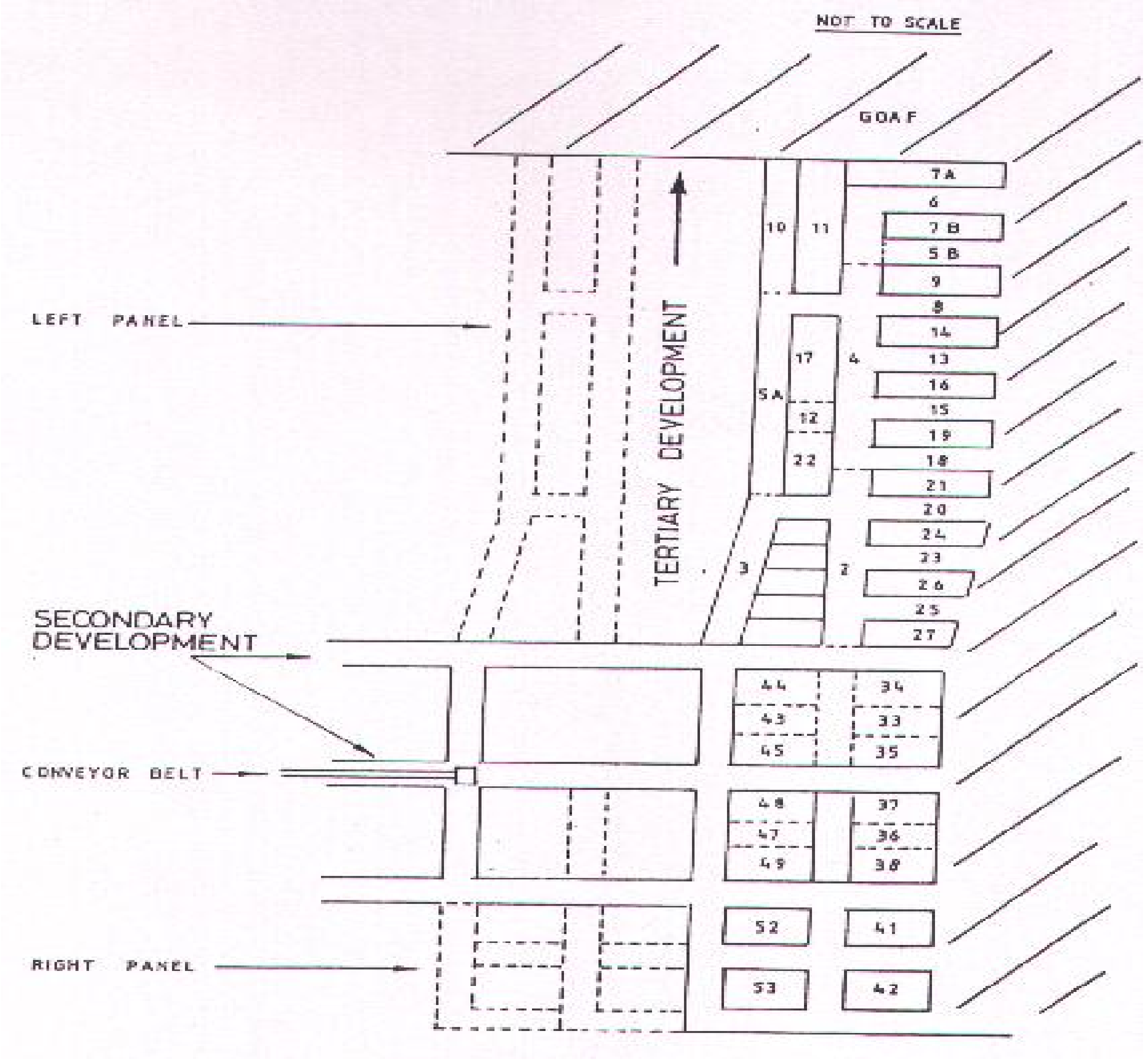


Figure 0–3 The Old Ben mining method (after Beukes, 1989)

Chase *et al.* (1997) describe various pillar-extraction methods employed in US coal mines, viz. the Christmas tree and outside lift, which will each be discussed in turn.

1.7.4 The Christmas tree method

This method is employed under deep cover when pillars on 18 or 24-m centres are required to maintain the necessary stability factors. Figure 0–4 depicts a common sequence in which lifts are extracted during barrier and production-pillar extraction. This layout shows the use of mobile powered supports. Since the area most prone to roof fall in pillar extraction is the intersection, use of mobile powered supports can enhance the stability of these areas, and allows non-essential personnel to retreat further from the goaf edge.

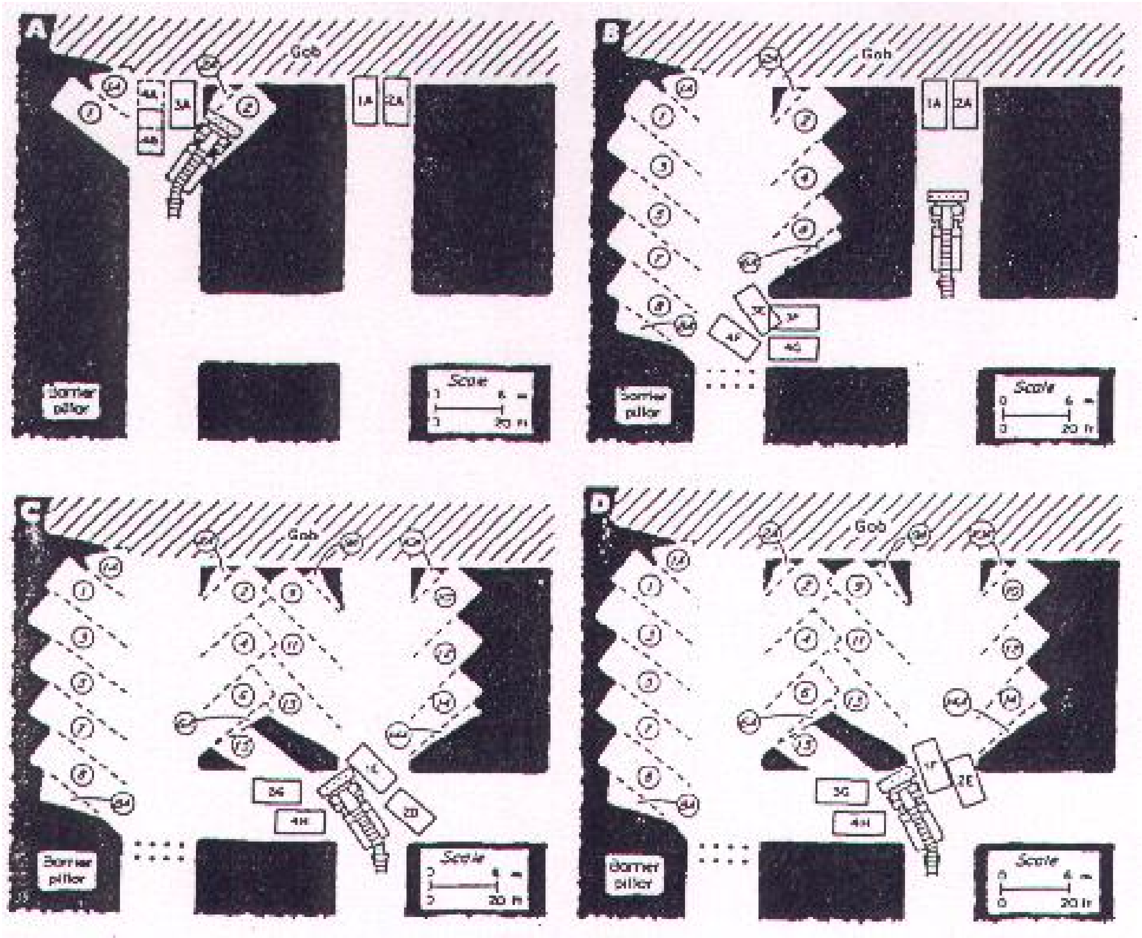


Figure 0–4 The Christmas tree extraction method. A, lifts 1-2A. B, lifts 1-8A. C, lifts push; pushout removal units 1 and 2 in tandem. D, lifts 1-push; pushout removal with units 1 and 2 staggered (after Chase et al., 1997)

1.7.5 The outside lift method

This method is generally used under less than 120 m of cover. Entry spacings are typically about 15 m, with cross-cuts on 25 to 37-m centres. Since these pillars have both a long and a short axis, they contain less coal and a large amount of time is spent tramming machinery. Chase *et al.* (1997) argue that this method is safer than the Christmas tree method. This is so, they claim, in areas under weak roof conditions because the unsupported span of the mined-out area is smaller than with the Christmas tree method. The main disadvantage of this method compared with the Christmas tree method is that the lift lengths are usually deeper, and prolonged exposure while mining them subjects the continuous miner to greater risk. Figure 0–5 shows a typical outside lift sequence.

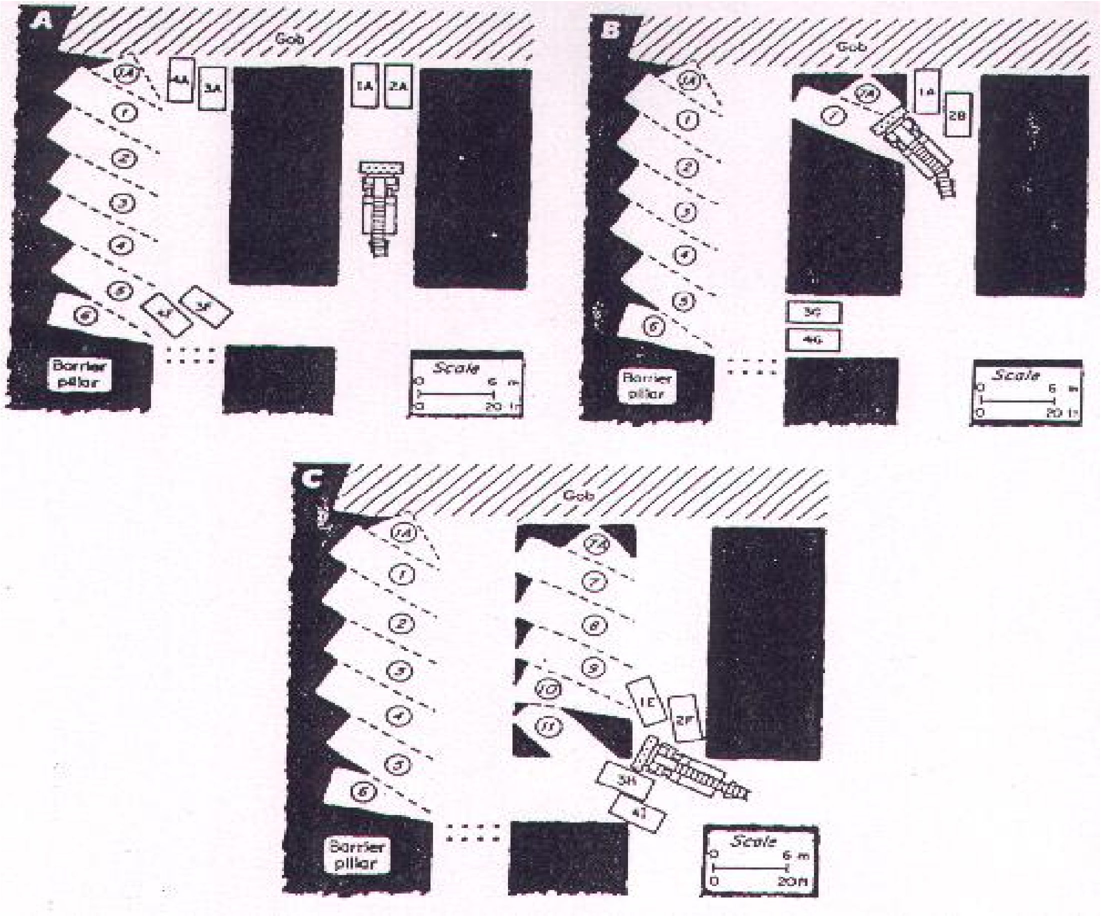


__Figure 0–5 Outside lift method. A, lifts 1-6; B, lifts 1-7A; C, lifts 1-push (after Chase et al., 1997)__

The Christmas tree and outside lift methods have been used successfully in combination to extract parallelogram-shaped pillars developed by continuous haulage, called the herringbone panel design. Chase *et al*. (1997) further describe variations of these total pillar-extraction techniques, and also discuss partial pillar-extraction techniques.

1.7.6 Summary of findings of pillar extraction in New South Wales

The full and partial extraction methods as examined in New South Wales were all implemented and designed around specific economic and geotechnical requirements of the individual operations. The choice of a partial versus a full extraction system appeared to be based on the following factors:

- Surface subsidence
- Nature of the immediate 15 m roof
- Geological nature of the potential goaf zone

Of the three partial extraction operations detailed, Munmorah and Cooranbong were overlain by a massive conglomerate which created previous problems with full extraction systems such as windblasts which previously had damaged both life and equipment. Additionally, these two operations were undermining sensitive areas, which precluded them creating a goaf. Although no surface subsidence was expected, the limited subsidence measured was probably a result of these collieries operating in a soft floor environment which resulted in the panel consolidating into and punching the soft floor.

The operation at Clarence Colliery precluded full pillar extraction as a result of two aquifers overlying the coal seam, as well as the massive Triassic sandstone roof, which caused caving hazards similar to those of Munmorah and Cooranbong Collieries. Previous full extraction had broken these aquifers and resulted in the operation still having to pump 14 – 18 megalitres of water per day from the workings as a result of the continuous water inflow into the workings. This, together with the complex vertical joint sets in the lease area required a partial mining method to avoid the hazards associated with these geological occurrences.

These three partial pillar extraction-mining operations used modifications of pillar stripping, designed specifically at Cooranbong Colliery to maximise extraction without creating surface interferences. The introduction of this method has ensured an increase of the overall extraction at the collieries of between 25 – 50 percent. All three operations used a remote control Joy 12CM type continuous miner and 2 – 3 15 tonne shuttle cars. In all cases the continuous miner cutter head was 3.6 m wide during extraction (as opposed to 5.5 m wide during panel development) and, where applicable, the on board roofbolt drill rigs removed prior to extraction commencing. ABLS's were used at Munmorah and Cooranbong Collieries, but were not used at Clarence Colliery. The inference drawn from this is that at the mining depth, the massive sandstone roof and the comparatively low overall extraction at Clarence Colliery resulted in a sufficiently safe working environment to preclude their use.

Of the full pillar extraction operations, two utilised modified Wongawilli methods designed to suit their individual conditions. At Bellambi West Colliery this was the most suitable extraction method given the pre-developed nature of the panel, while at Charbon Colliery the panels were specifically designed to accommodate this type of extraction. Of the other two full pillar extraction operations, Ivanhoe Colliery utilised an open ended system and United Colliery utilised an extraction method resembling the pillar stripping method, with the main difference being that the resultant fenders collapse rather than provide a support to the roof cantilever. This implies that this pillar stripping can be used for both full and partial extraction, with the failure mechanism of the method being the competence of the immediate overlying strata. All of the full extraction operations visited had no restriction on the amount of surface subsidence that they created. All four operations operated under either predominantly sandstone or mudstone roof which readily caved and closely followed the line of extraction. There was no sterilisation of economic reserves as result of the full pillar extraction operations. The rib spall at Ivanhoe Colliery was assumed to be primarily a factor of the age of the pillars, although additional factors could have contributed to this. The rib spall at United Colliery was attributed primarily to the geometry of the panels in relation to the seam dip, which resulted in unusual, and high abutment stresses. Little rib spall was associated with the modified Wongawilli methods as these, as described before, extract the pillars as they are created, limiting the effects that time might have on them. All the full pillar extraction operations employed remote controlled Joy CM12 continuous miners (all with a 3.6 m wide cutter head) with either 2 or 3 15 tonne capacity shuttle cars and 2 or 3 remote controlled ABLS's. In instances where there were on-board roofbolting rigs, these were removed prior to extraction commencing.

Both the full and partial pillar extraction operations conducted lifting of pillars on retreat and at an angle of 60°.

On the whole, issues pertaining to safety and cost of the operations could not be obtained as the information was of a confidential nature. In the 1999/2000 financial year however, 3 fatalities occurred on mining operations in New South Wales with a lost time injury frequency rate of 43 and a lost time injury incidence rate of 9 for underground operations (Anon, 2001). These figures are consistent with those reported for the 1998/1999 financial year. As for the cost aspect, the operations attributed the absence (or lower usage) of roof support, lower consumption of continuous miner picks and lower labour (usually 2 – 3 less than a development bord and pillar section) during extraction as factors contributing to operating costs being generally lower during pillar extraction.

The overall review of the pillar extraction operations in New South Wales as presented here highlights some of the more casual and general issues surrounding the choice of extraction method.

1.8 South African experience

At the shallow depth of coal mining in South Africa, there is considerable potential for improving the percentage extraction by utilising pillar extraction (Wagner and Galvin, 1982). Beukes (1989) states that pillar extraction in South Africa by handgot methods has been practised for many years. Pillar extraction with mechanised equipment commenced during the late 1960s, and approximately a decade later continuous miners were introduced into pillar and rib-pillar extraction. Livingstone-Blevins and Watson (1982) state that pillar extraction in South Africa can be practised using two methods, namely “open end” and “pocket and fender”.

1.8.1 The open-end system

Livingstone-Blevins and Watson (1982) have the following to say about this mining method:

> *“In this method mining takes place directly next to the goaf, creating a completely open side. Lifts or slices are mined straight through to the goaf and the whole pillar is extracted by a series of slices until only a ‘snook’ remains. The ’snook’ is extracted by a last cut or two, or is destroyed, or left to crush under the weight of the caving. The immediate roof over the slice is supported by its own cantilever strength, supplemented by systematic support in the roadways. Additional support and protection are installed next to the goaf line.*
>
> *“Generally, the support is withdrawn and the roof allowed to cave after completion of one lift before commencing the following one. In continuous miner installations where whole pillars are extracted in a single lift, it may be necessary to support large areas of roof before goafing. In large pillars, lifts are allowed to goaf, and mining sometimes takes place from alternating sides of the pillar to give continuity of production, and a protective coal barrier is left between the working area and the caving ground.”*

1.8.2 The pocket-and-fender system

Livingstone-Blevins and Watson (1982) state the following about the pocket-and-fender mining method:

> *"The basis of this method is to leave a portion of the pillar unmined, possibly to be taken later, but under no circumstances to be left in the goaf. A drive is mined into a pillar, leaving a 'fender' of coal between the drive or 'lift'. This fender is thin and usually is left to crush or is destroyed. Alternatively, it can be much thicker and is mined or partially mined at a later stage by driving 'pockets'. Fenders left at the end of the pillar should be of such dimensions as to allow limited convergence through controlled yield without collapse, so as to act as a breaker line extension. Fenders and snooks should crush readily after the withdrawal of artificial support; otherwise they should not run parallel to a geological weakness, i.e. cleats, fissures and faults. The roof is allowed to cave after completion of the lift and fender robbing before commencing the next lift."*

The choice of method is mainly dependent on the prevailing roof conditions. Ideally, an open-end system will be chosen whereby cuts are mined from one or two sides of the pillar adjacent to the goaf. In less favourable conditions, the pocket-and-fender system tends to be preferred whereby cuts are mined in the same way as in the open-end system, except that a fender or rib of coal (or a number of small coal snooks) is left adjacent to the goaf to serve as a temporary local support and protection.

1.8.3 Usutu method

In the Usutu method of pillar extraction, panels consisted of 9 roads at 19m pillar centers. Bord widths were 6m, leaving pillars of 13m square. At depths ranging between 110m and 140m below surface, it resulted in factors of safety of between 2.4 and 2.8.

The systematic roof support in panel development consists of 3 resin roofbolts per row, spaced at a 2m square grid. Roofbolts were either 1.2m or 1.5m long.

Pillar extraction was always done at a 45 degree stooping line. Extraction of pillars always started at the top end of the line as depicted in Figure 0–6.

The detailed extraction sequence of each pillar as well as the support sequence is depicted in Figure 0–7.

Timber breaker lines BL1 and BL2 and finger lines FL1 and FL2 are already in position as they are installed before the previous pillar was extracted. The first cut is then made and whilst finger line FL3 is being installed, the second cut is made on the opposite side of the pillar. Cut 3 is then made whilst finger line FL4 is installed. Cut 4 is made whilst finger line FL5 and breaker line BL3 are installed and finger line FL3 is extended. The continuous miner then has to wait whilst finger line FL6 is installed and finger line FL4 is extended before making cut 5. When this cut has been completed, the continuous miner moves to the next pillar to be extracted and breaker line BL4 is installed. All breaker lines and finger lines, except BL3 and BL4, are then extracted. (Beukes, 1989).

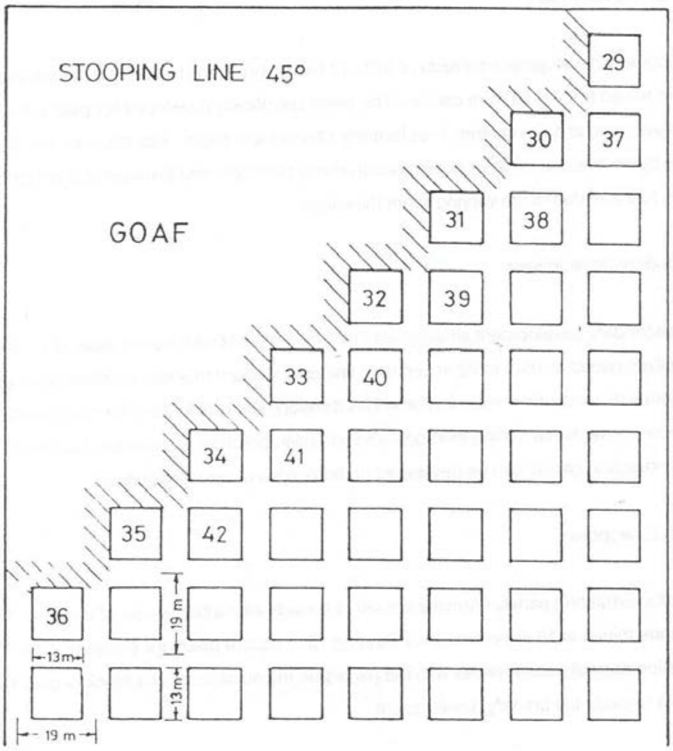


Figure 0–6 Usutu pillar extraction sequence (After Beukes, 1989)

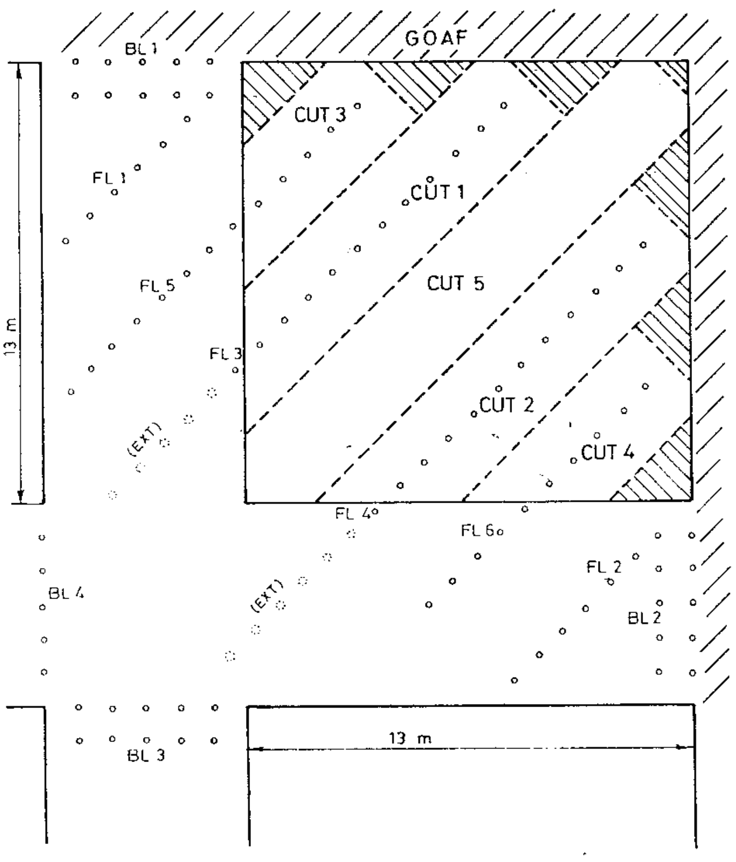


Figure 0–7 Usutu pillar extraction method and support (After Beukes, 1989)

1.8.4 Rib pillar extraction in South Africa

During the 1960s, only 11 per cent of total reserves at Sigma Colliery were extracted. Stooping experiments using conventional methods were employed, but these were unsuccessful as the friable roof conditions at the colliery made conventional stooping hazardous. A longwall system was then introduced in 1967 using chock supports, but this also proved to be unsuccessful. A complete longwall was installed and achieved world-class performance, but the method was only useable in localised areas. An investigation into the pillar-extraction methods used in Australia resulted in rib-pillar extraction (modified Munmorrah method) being introduced in 1980 in the No 2B coal Seam. By 1982 a double continuous miner section on the No 3 Seam had been established, based on the 1980 trials which proved a great success.

The primary development at Sigma consisted of four roadways from the main development to the limit of the remnant. The two outer roads were used as return airways, and the two inner roads as travelling and conveyor belt roads. The inner roads also served as intake roads. The secondary development consisted of three roads, two being intake airways and one a return airway. Cross-conveyor installations were used to minimise the tramming distance for shuttle cars. Several combinations of rib-pillar mining were employed at Sigma Colliery. De Beer *et al*. (1991) and Beukes (1989) give details of these. A typical rib-pillar extraction layout used is shown in Figure 0–8.

Rogers (1989) gives details of similar novel, but not unique, practices for rib-pillar extraction mining at New Denmark Colliery. Gericke (1989) discusses rib-pillar mining as conducted at Middelbult Colliery.

Beukes (1989) provides the following list of factors that determine the success of rib-pillar extraction:

- Pre-development of fenders must be carried out accurately to ensure uniform fender width.
- The length of fenders should be design for the behaviour of the overburden strata and the mining height to avoid premature failure.
- Fenders must be extracted as completely as possible to avoid stress on adjacent fenders.
- Breaker lines must be installed correctly.
- The final positions of fenders are high risks.
- Geological discontinuities must be pre-supported.
- A steady rate of advance must be maintained to avoid stress build-up.
- Timber props are less effective as breaker-line support when the mining height exceeds 3.5 m.

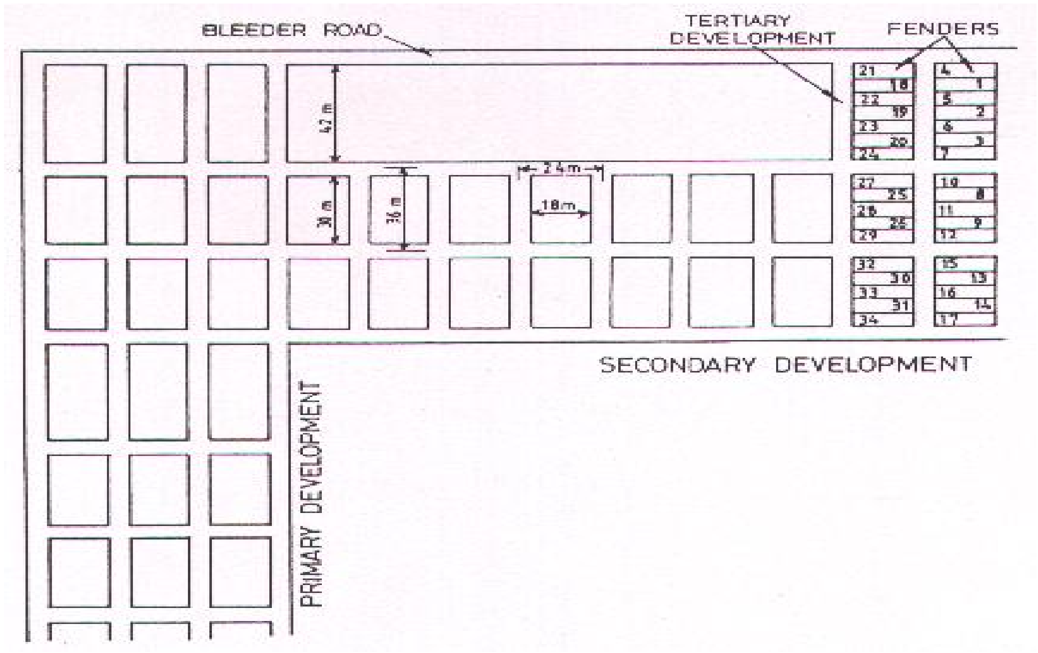


Figure 0–8 Rib-pillar mining method layout (after Beukes, 1989)

1.8.5 Advantages of the rib-pillar system

Beukes (1989) also gives some advantages of the rib-pillar system:

- A high percentage extraction is achieved.
- Rib-pillar extraction is an effective mining method for extracting small reserves of irregular shape that are difficult to mine using other methods, making it a flexible mining method.
- Mining activities are concentrated in a single working area, thus resulting in improved supervision.
- Coal is extracted from a stress-relieved area.
- Fewer intersections are created than with conventional pillar extraction, thus reducing the risk of roof falls.
- Continuous miner operators are always under supported roof.
- The capital cost is low in comparison with longwalling, and the working and maintenance costs are lower than those for bord-and-pillar mining.
- The ventilation that flows over the goaf serves to remove the dust and gas from the section during fender extraction.

Wagner (1981) adds the following advantages of the rib-pillar method of mining:

- The narrow rib pillars are formed immediately before they are removed and, consequently, these pillars are exposed to high stresses only for a short length of time.

Since the strength properties of highly stressed coal pillars deteriorate with time, it follows that these pillars are stronger than pillars of similar dimensions that have been standing for a longer period of time.

- The coal seam in the neighbourhood of these pillars has not been weakened by the development of a regular grid of bords as in the case of conventional bord-and-pillar mining with subsequent extraction.
- Mining equipment and personnel can operate from a well-supported bord.

1.8.6 Disadvantages of the rib-pillar system

- Once the extraction of a fender has commenced, it must be extracted completely before there is a long break in extraction time (e.g. a weekend) to prevent pillar failure.
- Ventilation problems can be experienced when the goaf closes up completely, thereby preventing bleeding over the goaf.
- Methane may build up in the goaf areas.
- Spontaneous combustion may occur in the goaf areas.
- There is a risk of roof falls on the continuous miner when extracting the final portion of a fender.

1.9 Factors constraining pillar extraction

1.9.1 Ventilation

Pillar extraction is vulnerable from the point of view of ventilation in that the air quantities should generally be greater than those employed in conventional bord-and-pillar mining and must be sufficient to dilute the expected outflow of noxious and/or flammable gas from the goaf (Plaistowe *et al.*, 1989). Livingstone-Blevins and Watson (1982) add that dust from continuous miner sections also needs to be taken into account.

Plaistowe *et al.* (1989) also list the following considerations with regard to goaf ventilation:

- Greater volumes of air are required to maintain air velocities in the last through road due to leakage through the goaf area.
- Continuous monitoring of methane, carbon monoxide and air velocities is necessary.
- Changes in barometric pressure have an effect on the air-gas mixture in the goaf area as the changes cause fresh air to enter, or a dangerous mixture of air to flow out of the

goaf areas. Fresh air entering a goaf area will supply oxygen, which in turn enhances the possibility of spontaneous combustion taking place within the goaf.

- During the caving of the overlying strata, there may be a 'dome effect' along the centre of the panel being extracted. Methane could collect in such a cavity and will not be cleared by the normal ventilation current. Rock falls in the goaf may be accompanied by frictional heating, which can result in methane ignitions.
- Mining at shallow depths in particular leads to disturbance of the surface strata, with major cracking. Fresh air entering the goaf via these cracks supplies oxygen, which, in turn, enhances the likelihood of spontaneous combustion taking place.

Beukes (1989) adds that if considerable quantities of gas are present in the seam or overlying strata, it is advisable for individual panels to be sealed off once extraction has been completed to prevent gases from entering the adjacent panels.

Livingstone-Blevins and Watson (1982) mention three general methods used for ventilating pillar-extraction sections:

1. Coursing ventilation in the section
2. Coursing the return air along the goaf line
3. Bleeding the return air, or a portion thereof, through the goaf itself to an established return airway behind the goaf.

The second method has found favour in continuous miner sections, exploiting the permeable nature of the loosely caved goaf to clear dust, gas and used air away from the section and not through the section.

1.9.2 Spontaneous combustion

When coal is left in the goaf, the risk of spontaneous combustion increases (Livingstone-Blevins and Watson, 1982). Early efforts at pillar extraction were followed by mine fires initiated by the spontaneous combustion of broken coal left behind, or of carbonaceous shales exposed in the roof strata, and were assisted by air admitted through induced fractures extending to the surface. Further, where other seams overlie the seam being mined by total extraction, the upper coal will be fragmented, leading to exposure to air with the subsequent danger of spontaneous combustion. Under these circumstances, either pillar extraction cannot be implemented, or steps must be taken to contain combustion.

1.9.3 Rock engineering aspects

1.9.3.1 Roof support

Breakerline support has successfully used in pillar extraction in South Africa. The purpose of breaker line supports in pillar extraction is to prevent the roof collapsing from the goaf side into roadways. There are three types of breaker lines: timber props, roofbolts and mobile breakerline support systems.

Although timber props were used in the past, currently almost all pillar extraction is done using roof bolt breakerlines. Livingstone-Blevins and Watson (1982) suggested that certain conditions must be fulfilled, irrespective of the type of support used in pillar extraction:

1. The method must provide adequate support to the workings during primary mining and allow for abutment stresses during subsequent pillar extraction.

2. An effective breaker line must be provided to limit the extent of caving, and must be constructed at the goaf edge, before every intended goaf and during subsequent exposure of the goaf during the next lift.

3. As production tempos increase, the speed of installation of the support must be increased to keep up with the extraction rate.

4. The installed support should not interfere with the movement of machinery during the pillaring operations.

5. Local support in the workings can only be expected to hold up the immediate roof.

Timber supports were most frequently used in pillar extraction in 1970s and 1980s, because of the simplicity of installation, and their relatively high load offering at small compressions (Livingstone-Blevins and Watson, 1982). The converse to this is that timber cannot provide a consistently high load during continuing compression. Their suitability for use in high seams is also questioned, since at height the timber buckles and snaps rather than compresses. Therefore, currently almost all the mines practicing pillar extraction use roofbolt breakerlines and fingerlines during the extraction.

The main advantages of roof bolt breakerlines are (van der Merwe and Madden, 2002):

- Low cost compared to alternatives
- Can be installed during the development phase, meaning that people are not exposed to the goaf during installation, as with standing props
- No disruption to the mining activities
- Independent of mining height, while timber props have to be thicker the longer they are.

Powered (mobile) supports are shield-type support units mounted on crawler tracks. They can be used during pillar extraction and eliminate the setting of the roadway, turn and cross-cut breaker posts that are required during pillar-recovery operations. They are a more effective ground support than timbers, and their use enhances the safety of section personnel and reduces materials-handling injuries (Chase *et al.*, 1997). The authors add that the use of powered supports reduces human errors and provides consistency in the effectiveness of installation. Livingstone-Blevins and Watson (1982) state that the size and weight of such units in confined spaces creates additional problems. However, their size does improve their stability. Chase *et al.* (1997) report that powered mobile supports are being increasingly used in US coal mines. Powered supports have also been used extensively in Australia (Livingstone-Blevins and Watson, 1982).

In addition to the above, Chase *et al.* (1997) list the following additional advantages of mobile supports:

- They enable personnel to remain further outbye the pillar line and reduce their exposure to the goaf overruns and rib (pillar) spalling.
- They are active supports and provide better roof coverage.
- They are better suited to handling eccentric loads (i.e. horizontal and lateral loading), which are common during pillar extraction.
- Their size gives them stability, so shuttle cars or personnel cannot knock them out accidentally.

1.9.3.2 Pillar design

Coal pillar design is of primary importance for the safe, economical extraction of a valuable natural resource. Initially, pillar dimensions and road widths were based on experience obtained through trial and error. Some of the errors committed have had disastrous consequences in terms of loss of life, equipment and coal reserves (Bryan *et al*., 1964; Madden, 1987).

On 21 January 1960 at 19:30, 437 people died in what has become known as South Africa's largest-ever mining disaster, the Coalbrook disaster. On that day 750 acres of ground subsided onto the No 2 Seam, which resulted in the collapse of 7 000 pillars, 4 400 within a five-minute period. Bryan *et al.* (1964) documented the accident well. At Coalbrook there was never any intention to extract the pillars by a second working. The long barrier pillars, with a width no greater than that of the ordinary pillars, were not designed with special roof-control measures, but were designed to help in the supply of adequate ventilation to the working panels, as well as to facilitate the sealing-off of these panels in the event of spontaneous combustion. Before 1950 there had been little mining in excess of 3 m in height at Coalbrook, but following the erection in 1955 of a large electricity-generating station close to the colliery, a considerable increase in demand was experienced and a mining height of 4.2 to 4.6 m became general practice. Panels that had been sealed were reopened and top-coaled to meet the increase in demand. This was done with little or no roof support until a decision was taken in 1958 to support the top-coaled areas. Mark *et al.* (1999a) further document other pillar collapses from around the world.

The inquiry following the Coalbrook disaster revealed that no proven method for the design of bord-and-pillar workings existed at that time anywhere in the world (Salamon and Wagner, 1985). A programme of research was initiated in 1963 focusing on the design of bord-and-pillar workings in South Africa, and the results were published in 1967 (Salamon and Munro, 1967; Salamon, 1967). Salamon and Munro (1967) derived a formula that defined approximately the strength of coal pillars in South African collieries. This formula was empirical in nature, being based on data obtained from a survey of actual mining dimensions, and included information on stable and collapsed areas of mining. The analysis of pillar design was based on the concept of a safety factor, S, defined by the equation:

$$S = \frac{Pillar\ Strength}{Pillar\ Load}$$

where *strength* is taken to mean the strength of the pillar and *load* the average pressure acting on the pillar. When actual values are substituted into the above and it is found that

$S>1$ or $S<1$. then these values of S can be taken to indicate that the pillar will be stable or will fail respectively (Salamon and Munro, 1967). Further, if the strengths and loads are predicted in some manner for a large number of cases in which pillar failure is subsequently observed, it will be found that the safety factors calculated from the predicted values are scattered - provided the predictions are unbiased - around unity (Salamon and Wagner, 1985). The safety factor at which failure occurs is assumed to be denoted by S_c. The exact value of S_c will not be known in advance, but the aim of pillar design is to secure, with an acceptably high degree of probability, that $S> S_c$.

Steart (1954) derived an expression based on laboratory testing for the strength of coal pillars. Other authors cited by Salamon and Munro (1967) have developed similar expressions and empirical formulae for other rock types. The strength of a pillar depends on the strength of the material of which it is composed, its volume and its shape (Salamon and Munro, 1967). The pillar strength formula that occurs most commonly in the literature is a simple power function composed of the volume of the pillar (in terms of its width, *w*, and its height, *h*) and the effect imposed on the pillar by the roof, by floor friction and by cohesion. Salamon and Munro (1967) suggest the following variation of this formula as:

$$Strength = Kh^{\alpha} w^{\beta}$$

where K, α and β are appropriately chosen constants, the values of which are defined as 7 200, -0.66 and 0.46 respectively by Salamon and Munro (1967). They further define K as the strength of a unit cube of coal, the limitation being that this value would represent all coal seams mined in various collieries. Madden (1989b), in his reassessment of the work conducted by Salamon and Munro (1967), found that there was no statistically significant difference between the strengths of individual seams so that the average strength could represent all seams. He states that this may be the result of the anisotropic nature of coal and the influence of local variation in material properties, as well as relating to structural effects.

The load as mentioned above is calculated using the 'tributary area'. The limitation of Tributary Area Theory is requires a reasonably uniform geometry and applicable where the panel width is greater than the depth below surface; each individual pillar is then assumed to carry the weight of the overburden above it. Load is thus calculated by:

$$Load = \frac{25HC^2}{w^2}\ (kPa)$$

where H is the depth of the floor seam (m)
w is the pillar width (m)
C is the pillar centre distance, the sum of the pillar and bord width (m)
25 is the multiple of the overburden density and gravitation.

The above two equations can be combined to obtain the safety factor:

$$S = 288\frac{w^{2,46}}{Hh^{0,66}(w+B)^2}$$

After reviewing all pillar collapses and undertaking a statistical analysis of these findings, Salamon and Munro (1967) achieved the empirical determination of the above formula. Madden (1989b) conducted a reassessment of this formula in the hope that it could be applied beyond the empirical range for which it was derived. Using the same criteria as Salamon and Munro (1967), he examined the 31 pillar collapses that had taken place since the introduction of the pillar design formula (during the period 1966 to 1988). He isolated the collapses caused by load failure and compared them with the results of Salamon and Munro (1967). Madden found little variation between the later and earlier collapses, and that the later pillar collapses in fact reaffirm the results of the earlier pillar collapses rather than showing a new trend. His findings showed that no pillar collapse had been reported in which the width-to-height ratio was greater than 4.0. He also found that two-thirds of the collapsed pillars had an area percentage extraction of greater than 75 per cent.

The time between mining and pillar collapse versus the safety factor indicates that it takes a considerable time for pillar collapse to occur (Madden, 1989b). Among the cases for which this time was known, 50 per cent collapsed within four years of mining.

Madden (1989b) identified two significant features from his analysis of the collapsed pillars:

1. Pillars at depths of less than 40 m, with widths of less than 4 m and an extraction above 75 per cent, are prone to pillar collapse even when their designed safety factor is higher than 1.6.

2. No pillar collapse has been recorded for pillars with width-to-height ratios greater than 3.74. This suggests that the pillar design formula underestimates the strength of a pillar as its width-to-height ratio increases.

More recent work by Madden and Canbulat (1996) examined pillar collapses from 1988 to 1996. The researchers identified 21 additional collapses of this nature during this time. The results of these analyses showed that pillars with width-to-height ratios of up to 4.3 had collapsed, and that in certain cases the time from mining to collapse was more than 20 years, thus highlighting the long-term stability aspect of pillar design. They add further that Salamon's original formula is applicable within his original range, but that long-term collapses are occurring in pillars with low safety factors and that regional characteristics are influencing pillar stability.

Research by Mark *et al.* (1999a) found that massive collapses in coal mines have the following characteristics:

- Slender pillars (with a width-to-height ratio of less than 3.0)
- Pillars with a low safety factor (less than 1.5)
- Competent sandstone strata
- Collapsed area greater than 1.6 hectares (4 acres)
- Minimum dimension of the collapsed areas greater than 110 m.

Madden, 1989b states that a limitation of the pillar strength formula is that it assumes that the strength of a pillar increases proportionately with a power of the width-to-height ratio, which is less than unity. He adds that this limitation was not evident in the statistical study done by Salamon and Munro (1967) because the case histories of collapsed pillars only included pillars with width-to-height ratios of 3.6 or less. Further, the present collieries and some of the new reserves currently being mined on older reserves are situated at depths of more than 150 m and up to 580 m (in Natal area), which extend beyond the empirical range of Salamon and Munro's statistical analysis. It was for this reason that Salamon in 1982 (cited in Madden, 1989a) extended his pillar strength formula to take cognizance of the increasing ability of a pillar to carry load with increasing width-to-height ratio, known as the 'squat pillar' formula.

1.9.3.3 Squat pillar formula

The extension of the pillar formula stemmed from the thinking that the pillar strength formula was conservative when the width-to-height ratio exceeded 5 or 6, and that a pillar with a width-to-height ratio of 10 was considered virtually indestructible (Salamon and Oravecz, 1976: cited in Madden and Canbulat, 1996). Wilson (1972: cited in Madden, 1990) suggested the ‘inner-core’ concept, which holds that the inner core of a large pillar is surrounded by and confined in a triaxial-type situation by both a failed and a yielded zone, thereby strengthening the pillar’s load-carrying capacity. The size of the central core increases with increasing width-to-height ratio (Madden, 1990).

Laboratory tests on sandstone samples to examine the suitability of the new formula, known as the 'squat pillar formula', for predicting the strength increase with increasing width-to-height ratio showed that the test results fitted the formula well.

The extension of the pillar strength formula beyond its empirical range therefore resulted in the squat pillar formula.

The strength of a pillar given by the squat pillar formula is:

$$\sigma_s = k\frac{R_0^b}{V^a}\left\{\frac{b}{\varepsilon}\left[\left(\frac{R}{R_0}\right)^{\varepsilon} - 1\right] + 1\right\}$$

where k is the unit strength of a cube of coal

R_0 is the critical width-to-height ratio

ε is the rate of strength increase

a is 0.0667

b is 0.5933

V is the pillar volume.

It is suggested that the squat pillar formula could be used with the critical width-to-height ratio (R_0) taken as 5.0 and that ε could be taken as 2.5. The assumption of 5.0 for R_0 is based on the fact that no pillar with a width-to-height ratio of more than 3.74 was known to have collapsed.

The general behaviour of samples tested using the squat pillar formula showed the following important results (Madden, 1988):

1. The strength of the squat specimens increases rapidly with increasing width-to-height ratio.

2. Violent brittle behaviour is characteristic of samples with low width-to-height ratios, but the mode of failure of samples with high width-to-height ratios is gradual and non-violent (i.e. ductile). The load increases with deformation.

The change from brittle to ductile behaviour at high width-to-height ratios is of great significance as far as the stability of bord-and-pillar workings involving squat pillars is concerned, in that the manner of failure changes (Madden, 1990).

The application of the squat pillar formula is seen in the absolute increase in area percentage extraction over the pillar strength formula (Madden, 1989b). The associated smaller mining geometries result in an increase in productivity due to shorter tramming distances, as well as the increase in coal extracted. The oversupply of coal on the world market and the rising costs of labour and storage have made it essential to keep the working costs of coal mined to a minimum. One way of reducing the cost of coal per ton mined is to increase productivity (Madden, 1989a).

1.9.3.4 Effect of pillar geometry

A coal pillar consists of the pillar itself, the roof and floor strata, and the pillar-roof and pillar-floor contacts. Pillar systems may collapse gradually or suddenly. In general, failures initiated by roof or floor failure develop gradually. Sudden collapses are usually associated with pillar system failures involving competent roof and floor strata, in which the coal pillar itself fails (Galvin *et al.*, 1997).

Spalling of the pillar sides may be caused by one or more of the following factors (Madden, 1988):

- Geological discontinuities
- Blast damage
- Weathering
- Presence of a weak layer in the pillar side
- Excessive stress on the pillar edge.

The effect of a single discontinuity (such as a slip) can be significant in pillars with low width-to-height ratios, but as this ratio increases, the influence of the discontinuity decreases (Madden, 1988). Small pillars are also affected by local weaknesses in sedimentation, which can cause frittering of a weak layer to extend up to 1 m into the pillar sides. The effect of frittering is more serious if there is a weak band in the roof, since frittering of the sidewall increases the bord width and may jeopardise the roof stability (Madden, 1990).

Blast vibration and the effect of the gases from explosions penetrating existing discontinuities damage the skin of a coal pillar formed by conventional drill-and-blast techniques (Madden, 1989b). Madden adds that fracturing reduces the strength of the perimeter of the pillar, resulting in a zone of weakness that is not present in pillars formed by continuous miners. In time, this weakened zone spalls from the pillar side and reduces the width of the pillar. The depth of blast damage into the side of a pillar has been quantified by Madden (1987) as being between 0.25 and 0.3 m. The pillar strength formula developed by Salamon and Munro (1967) was based on a statistical analysis of case histories of bord-and-pillar workings, all of which were mined using the drill-and-blast method. Madden (1987) highlighted the fact that this analysis was based on the designed mining dimensions, implying that the coal pillar strength formula derived by Salamon and Munro indirectly takes into account the weakening effect of blast damage. He continues by saying that the effective width of a pillar is therefore as designed according to the pillar design formula of Salamon and Munro (1967) *but not* necessarily as mined by a continuous miner. Madden further states that this effective pillar width when mined by a continuous miner is greater by an amount approaching the extent of the blast zone, than that of a pillar formed by drilling and blasting. Since approximately 80 per cent of South Africa’s coal has been mined using bord-and-pillar mining, the implications of this pillar design anomaly are that a large volume of recoverable coal is left in pillars designed using the pillar strength formula of Salamon and Munro (1967).

Wagner and Madden (1984) derived an expression for the safety factor of bord-and-pillar workings developed by means of a continuous miner:

$$\eta = \eta_0 \left(1 + \frac{2\Delta_w}{W_0} \right)^{2,46}$$

where η is the safety factor of a pillar formed by a continuous miner

η_0 is the safety factor of a pillar formed by drilling and blasting
Δ_w is the extent of the blast damage
W_0 is the nominal pillar width.

The significance of this expression is that it shows that extraction can be increased where the reduction in pillar width does not result in excessive stress concentration over the edge of the pillar. It is further noted that it is the strength of the coal pillar formed by a continuous miner that is being adjusted by this method, not the safety factor design formula. An additional result obtained by Madden (1989b) in testing blast-zone damage concerned the effect of the stability of the immediate strata. Since blast damage causes pillar widths to decrease and hence bord widths to increase, the strength of the immediate overlying strata is crucial to the stability of the area.

Wagner (1974) states, with regard to stress on the pillar edge, that the corners and sides of pillars are independent of the width-to-height ratio.

Livingstone-Blevins and Watson (1982) mention that in older workings the original dimensions of the pillars may be small and, upon extraction, the increased abutment load may be dangerously close to the crushing strength of the pillar. Under these conditions, extraction of the pillars is therefore not advisable. They do not mention any limitations on this however. They make further mention of the effect of the time lapse between primary mining and subsequent extraction, stating that rapid extraction can preclude roof problems caused by deterioration with time.

1.9.3.5 Strata control

Livingstone-Blevins and Watson (1982) state that it is in the abutment zone that pressure problems occur, that the position of peak abutment varies from location to location and that the zone may extend over a large area. Cantilevering of the roof beams over the working mining area before the beams cave causes abutment pressures; the magnitude of the stress depends on the length and thickness of the roof overlying the goaf area.

They provide a list of areas where high stresses can be expected in a pillar-extraction section, thus highlighting critical areas of high risk:

- Areas close to the extraction line
- Pillar areas close to wide bord ways

- Pillars that are larger than surrounding pillars
- Projections on active pillar lines or pillar lines moving parallel to old goaf areas
- Mining seams in which the coal and adjacent strata have very different physical properties.

They further identify the roof conditions necessary for the correct design of a pillar-extraction section, as follows:

- The local roof strata must be able to bridge bord and constantly widening diagonal spans safely.
- They must be capable of undergoing convergence deflection during pillaring without failing.
- Together with the upper strata, they must allow early and regular caving to minimise cantilever effects and keep induced abutment stresses on the pillar line at a low level.

1.9.3.6 Surface subsidence

By creating excavations in a rock mass, mining inevitably induces displacements in the medium (Salamon and Oravecz, 1973). Total extraction induces subsidence on surface, the magnitude of which is determined by the bulking factor (Plaistowe *et al.*, 1989). The presence of surface structures and water accumulations will generally rule out pillar extraction. Surface subsidence may cause changes in the drainage and hydrology of the area. For this reason, when a mining method is being decided upon, cognizance must be taken of the presence of aquifers or aquicludes, and of the possible ingress of water into the workings. Galvin *et al.* (1981) state that all South African coalfields are overlain either by roof strata consisting of alternating layers of weak shales and moderately strong sandstones, or by roof strata containing one or several massive dolerite sills. They assert that surface displacements depend on the extent of the workings, their depth below surface and the physical properties of the rock mass. Furthermore, they are of the opinion that in South African coal seams that are less than 200 m deep and more than 1 m thick, some form of protection must be introduced if damage to the surface is to be avoided. They suggest the use of solid supporting pillars, packing or stowing, or protection by phasing of pillar extraction.

Livingstone-Blevins and Watson (1982) suggest that maximum subsidence occurs when an excavation exceeds a critical width. This critical width is related to the mining depth and is also affected by the bulking factor of the caving material, but varies from one coalfield to another.

Schumann (1982) found that shallow undermining of a surface railway structure by the method of total extraction could lead to controlled subsidence of the surface and might permit safe and uninterrupted rail traffic. He conducted measurements of surface ground movements while pillar extraction was taking place and concluded that continual monitoring and taking immediate corrective measures would allow the successful extraction of these pillars.

1.9.3.7 Geology

Plaistowe *et al.* (1989) noted that pillar extraction depends on the controlled caving of the immediate and upper roof beds. They suggest that the geology of the proximate and superincumbent strata will therefore dictate the feasibility of pillar-extraction techniques as well as subsequent panel and pillar design. (See list of geotechnical roof requirements above in Sub-section 3.5.3.1.)

Livingstone-Blevins and Watson (1982) further add that caving becomes more likely with greater depth because of the greater weight of the main roof. They further mention that pillar extraction beneath a potentially viable coal seam will tend to sterilise the top seam, which makes this practice undesirable. Plaistowe *et al.* (1989) fundamentally agree with this conclusion regarding the economic sterilisation of coal seams.

1.9.3.8 Design of suitable areas

Mark and Chase (1999) describe a computer model (called ARMPS) that can be used as an aid in the design of pillar-extraction operations. The goal is to ensure that the pillars developed for future extraction are of adequate size for all anticipated loading conditions. The main benefits of using this program are that potential pillar failures can be predicted, and that the associated unsatisfactory conditions can be avoided. The program predicts:

- Pillar squeezes, accompanied by significant entry closure and loss of reserves
- Sudden collapses of groups of pillars, usually accompanied by airbursts
- Coal pillar bumps (violent failures of one or more pillars).

This program requires six inputs from which it will calculate the safety factors for the entire Active Mining Zone (AMZ) rather than stability factors for individual pillars. This is based on the assertion that pillars behave as a system rather than displaying individual strength properties. The inputs into this system are:

1. Pillar dimensions (including angled cross-cuts, barrier pillars, varied spaced entries, etc.)
2. Depth of cover
3. Mining height
4. Entry width
5. Cross-cut spacing
6. Loading conditions.

Four loading conditions are identified, as shown in Figure 0–9. Loading condition 1, the simplest, is development loading only. Loading condition 2 occurs when an active panel is being fully retreated and there are no adjacent mined-out areas. The total applied load is the sum of the development loads and the front abutment load. Loading condition 3 occurs where the AMZ is adjacent to an old goaf and the pillars are subjected to development, side abutment and front abutment loads. Loading condition 4 is used where the pillar line is surrounded by goaf on three sides.

Heasley (1997) presents research conducted during the development of a laminated overburden in a displacement-discontinuity model (LAMODEL). He observes that a laminated overburden (with a low lamination thickness) is more flexible or supple than a homogeneous isotropic overburden. He further claims that the LAMODEL program can provide realistic stress and displacement calculations for a wide range of mining situations because of the flexibility of the laminated overburden model and the unity of the numerous practical features implemented in it.

The limitation of this program and other similar models is that they are not able to model areas that have already been developed. They are used primarily for the pre-planning of undeveloped areas that are potentially suitable for pillar extraction.

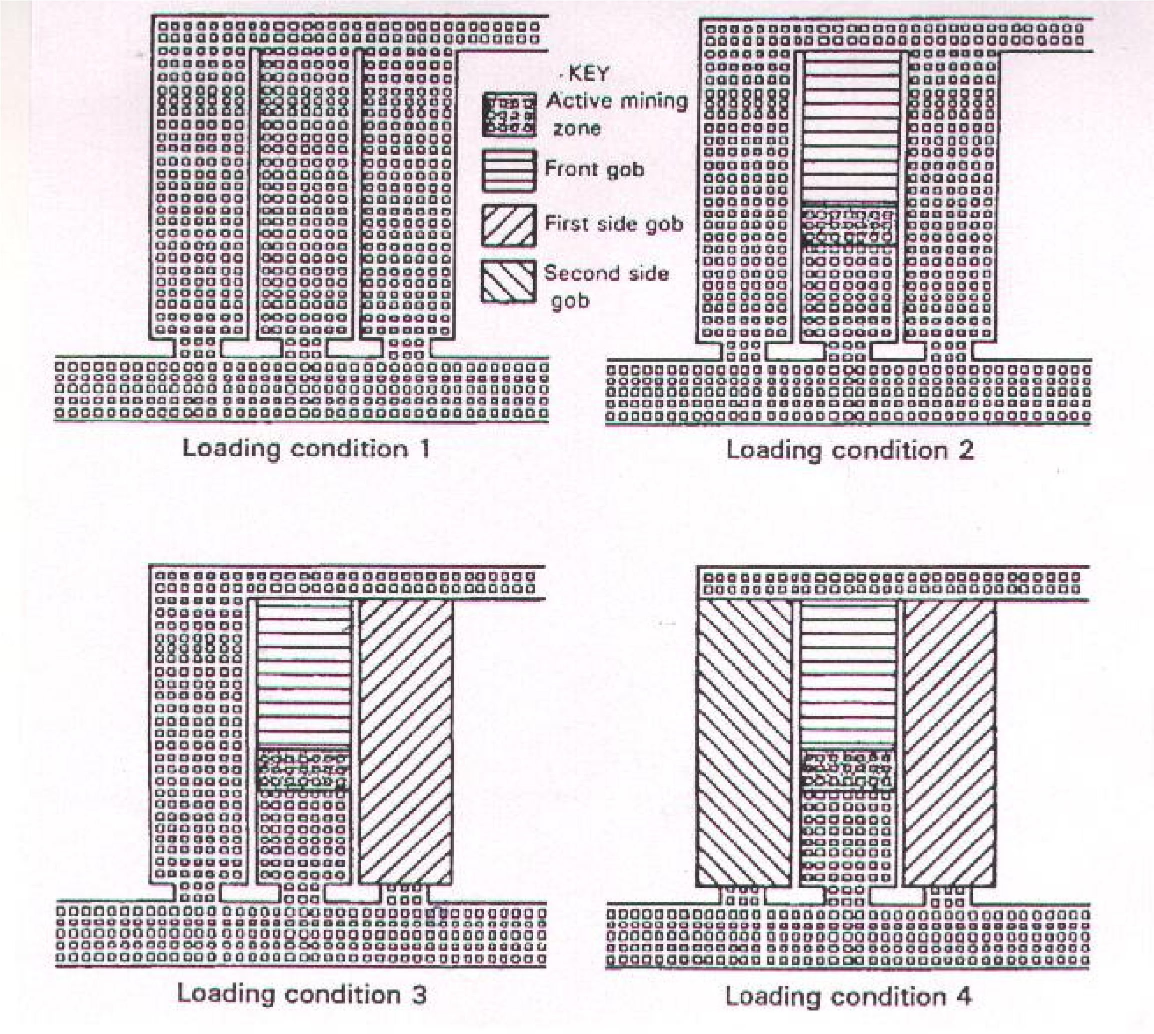


Figure 0–9 The four loading conditions that can be evaluated using ARMPS (after Mark and Chase, 1999)

Vervoort and Prohaska (1991) measured the closure during pillar extraction (and conducted three-dimensional numerical solutions on these measurements) to determine an efficient and cost-effective support system for intersections during pillar extraction. They found that:

1. During pillar extraction, the roof in intersections undergoes a cantilever effect, with the largest movement occurring at the edge of the pillar being extracted, and the smallest at the opposite edge.

2. During pillar extraction, the installation of cable bolts and cable trusses as supplementary support improves the roof stability by reducing the roof deflection.

3. The numerical solutions showed that, of the total elastic roof deflection in an intersection, about half occurs during the extraction of the adjacent pillar. The other half is the sum of the roof deflection during the development of the bord-and-pillar section and of the roof deflection prior to the extraction of the adjacent pillar.

1.9.4 Safety

The method of coal extraction has a considerable influence on the safety risk. Falls of roof and sidewall collapses have been a major cause of fatalities in South African collieries (Vervoort [1990a,b,c] and Canbulat and Jack [1998]). Roof falls seriously affect safety, cost and productivity in coal mines, and this means that labour, supplies and equipment have to be diverted from coal production for clean-up purposes, recovery and repair of mine equipment, and the re-supporting of the mine roof. Both direct and indirect costs are associated with lost production and the more emotional issue of loss of life is also significant (Marx, 1996).

The number of accidents over the past decade in the coal industry indicate that the safety risk, expressed as days lost, is over six times greater for underground mines than for opencast mines (Willis and Hardman, 1997). This difference between the two methods of coal extraction applies equally to the number of accidents, the number of fatalities and the number of people injured. Willis and Hardman (1997) add that falls of ground (rock engineering) and machinery/transport (engineering) are the main areas of concern since these two categories have together accounted for 99 per cent of incidents, 79 per cent of fatalities and 99 per cent of injuries. The remaining percentages in each case can be attributed to the areas of mine environmental control and occupational health issues. Ashworth and Phillips (1997: as cited in Madden, 1996) show that based on the accident data for coal fatalities and injuries over nine years, 9 per cent of all fatalities in the South African mining industry occurred on collieries, with fatalities and serious injuries being more common in underground than in surface operations.

A summary of coal mine accidents is given in Table 0–1. These data combine underground and surface accidents.

Vervoort (1990a,b,c) notes two important problems in interpreting such statistics:

1. Even if there are significant trends over a long period of time, there can be an abrupt change in an individual year without a change in the safety circumstances. Extrapolating such figures into the future may therefore provide inherent inaccuracies.

2. Over the years, many factors that have affected the fatality figures may change. Some of them, such as the training of people, and the support system and mining method used, have a direct influence on safety, whereas others, such as the total workforce and coal production, have a more indirect influence on the number of fatalities. Therefore, it is not always possible to find explanations for trends or for abrupt changes in them.

Table 0–1 Coal mines – Accident data 1984 to 1998 **(after Department of Minerals and Energy, 1999)**

Year	Fatalities	Fatality rate	Injuries	Injury rate
1984	73	0.67	796	7.26
1985	93	0.83	775	6.92
1986	67	0.61	688	6.21
1987	123	1.17	554	5.28
1988	55	0.55	372	3.71
1989	54	0.55	377	3.81
1990	51	0.53	400	4.16
1991	43	0.48	370	4.09
1992	46	0.65	358	5.04
1993	90	1.57	279	4.87
1994	54	0.96	240	4.26
1995	31	0.53	235	4.00
1996	45	0.75	285	4.77
1997	40	0.72	270	4.88
1998	43	0.5	257	4.46
1999	28	0.51	207	3.78
2000	30	0.52	213	3.70
2001	17			

In South Africa, different mining methods are used, the most common being bord-and-pillar, top coaling, stooping, longwall and rib pillar. The relative distribution of fatal falls of ground for the different mining methods for the period 1970 to 1988 is shown in Figure 0–10 (Vervoort, 1990a,b,c).

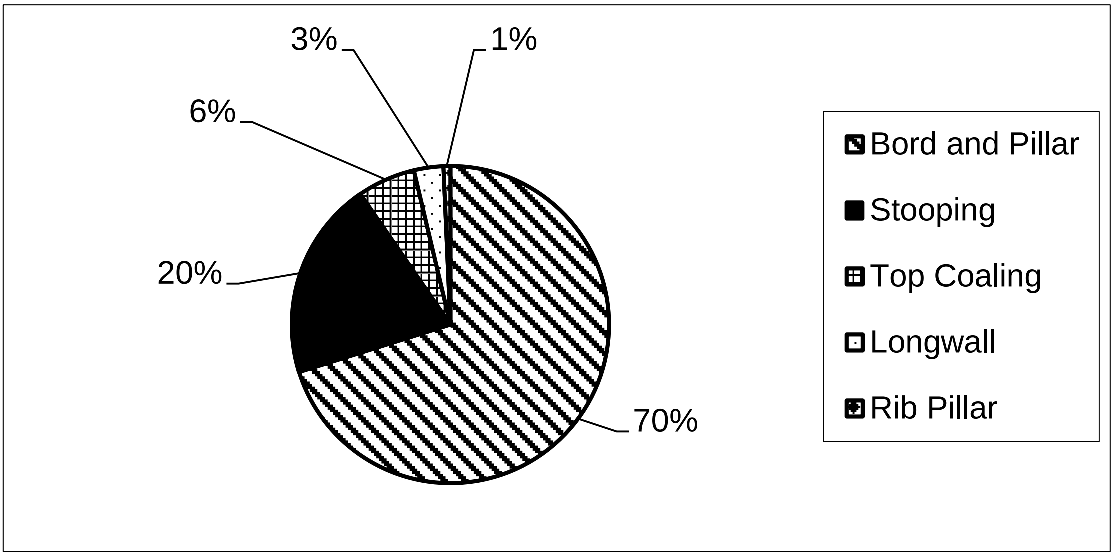


Figure 0–10 Relative distribution of fatal falls of ground for different mining methods (period 1970 to 1988)

This graph shows that the bord-and-pillar mining method was responsible for 70 per cent of all fatal falls of ground accidents for the period 1970 to 1988. It should be noted that bord-and-pillar mining is still the most frequently used exploitation method, which means that the level of risk of a fatal fall of ground accident will, of course, be higher. Vervoort (1990a,b,c) concludes that longwall mining is the safest and stooping the least safe method. He adds that bord-and-pillar mining lies somewhere between the two total extraction methods. Canbulat and Jack (1998) also concluded that based on the data analysed on falls of ground fatalities in South African collieries, stooping is the most dangerous mining practice with respect to production.

Vervoort (1990a,b,c) gives insight into the locality of falls of ground fatal accidents in relation to bord-and-pillar, stooping and top-coaling sections. Insufficient data for longwall and rib-pillar sections was available for analysis at the time. He found that the intersections of bord-and-pillar workings were the most dangerous, and cites the three-dimensional nature of these intersections as the main cause of instability. His findings on fatal falls of ground for different locations in bord-and-pillar workings are shown in Figure 0–11.

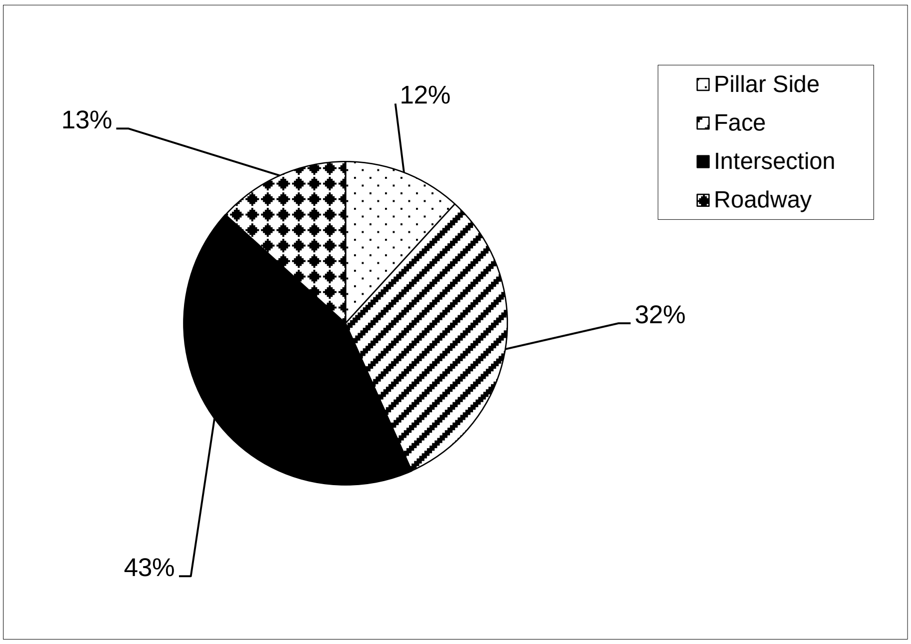


Figure 0–11 Relative distribution of fatal falls of ground for different locations in bord-and-pillar workings (period 1970 to 1988)

Figure 0–12 depicts Vervoort's (1990a,b,c) findings on fatal falls of ground locations in stooping sections, showing the relative distribution of each location over the period 1970 to 1988.

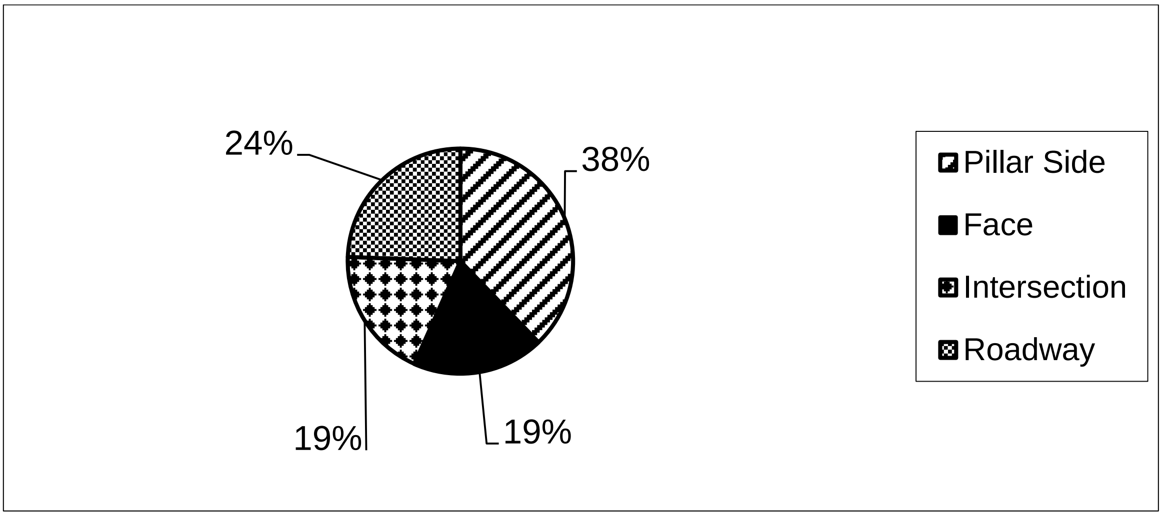


Figure 0–12 Relative distribution of fatal falls of ground for different locations in stooping sections (1970 to 1988)

In stooping sections, sidewall collapses account for 38 per cent of fatalities, which Vervoort (1990a,b,c) attributes to an increase in stress on the remaining parts of the pillars through which sidewall failure can occur.

In the period considered by Vervoort (1990a,b,c), only one fatality occurred as a result of a sidewall collapse, the others resulting from falls of ground in the intersections.

Mark *et al.* (1999b) reported that over the period 1989 to 1996, 33 deaths were the result of retreat pillar extraction. This figure represents 25 per cent of the total 111 roof and rib fatalities over the same period. They further reported that 45 per cent of the fatalities related to pillar extraction occurred when the continuous miner was cutting the last lift.

1.10 Conclusions

Various pillar extraction methods are applied successfully on a worldwide front. These methods include both methods for the secondary extraction of previously mined pillars as well as “pillars” designed and developed for immediate extraction such as the typical rib pillar methods.

It is critical to take note of the various constraints affecting successful pillar extraction both during the design phase as well as in the evaluation of previously mined pillars. Although it is well known that due to the dynamic nature of pillar extraction, and awareness of danger involved in pillar extraction, limited study into the investigation of falls of ground fatalities in South Africa indicated that pillar extraction is the least safe mining practice (Vervoort [1990], Canbulat and Jack [1998]).

Site visits

1.11 Background to site visits

1.11.1 Introduction

It is well known that the condition and safety factors of coal pillars that have been previously mined will deteriorate with time.

By investigating the mining layouts in which fatal accidents related to pillar extraction had occurred and examining the relevant accident reports, Oberholzer *et al.* (1997) arrived at various conclusions on the condition of the pillars being extracted in these cases. This involved case studies of 27 fatalities (from 1987 to 1996) in 15 producing panels.

1.11.2 Effect of the safety factor on accidents

The safety factors, as calculated from the Salamon and Munro formula, of the areas where the accidents occurred ranged from 1.4 to about 6.0. The frequency of accident occurrences against the safety factor and related production tonnages are shown in Table 0–1 below. It was thought that the safety factor in the areas where falls of ground accidents occurred might be a contributing factor to these accidents.

Table 0–1 Accidents and production related to the safety factor

Safety factor	Frequency of occurrences	Thousands of tons produced per month
1.0 – 1.5	0	0
1.5 – 2.0	7	262
2.0 – 2.5	16	523
2.5 – 3.0	1	6
3.0 – 4.0	1	5
+ 4.0	2	14

The statistics presented in this table show that the accident frequency does not relate directly to the safety factor, but rather to the tons produced. The results indicate more definitely, as would be expected, that most of the tonnage from the pillars extracted was mined at safety factors between 1.5 and 2.5, which was also the range within which most of the accidents occurred. Approximately 85 per cent of the accidents occurred at safety factors between 1.5 and 2.5 and 97 per cent of the tonnage produced were also in this range. The accident reports indicated that 85 per cent had occurred in the area directly related to the actual extraction operation and 15 per cent elsewhere in the section. These dramatic figures indicate that the major fall of ground hazard is the area where the pillar extraction is actually being done.

1.11.3 Condition of pillars in pillar-extraction sections

Pillars older than 10 years are likely to have been mined by means of conventional drill and blast and those from more recent years by means of continuous miners of either the drum or roadheader type.

Although the rib sides from blasting will be more uneven than those cut by continuous miners, general pillar conditions will be influenced by the local geology and stress levels rather than the mining method.

In the survey specific attention was given to the pillars immediately adjacent to the goaf line as mining retreated. These pillars were the most sensitive and gave the best indication of induced scaling due to pillar extraction.

Cases in which there was no scaling as well as cases in which there was severe scaling were observed in panels mined by both the drill and blast method and continuous miners. However, the severe scaling occurred where the safety factors were low. Roof conditions and support away from the stooping line were typical of the mines in which pillar extraction was done.

From informal discussions held with the personnel involved in pillar extraction, it was found that the most important human factors affecting the safety aspects associated with pillar extraction were: training, local knowledge and the discipline of the team of workers doing the pillar extraction. In addition to the safety factor, the general condition of the area and adequate support were of the major aspects taken into account, whereas the age of the pillars was not of a matter of particular concern.

The applicable observations and information from this exercise are summarised in Table 0–2 and Table 0–3 below, indicating that old pillars with low safety factor are more prone to scaling.

Table 0–2 Condition of pillars related to age

		Condition of pillars			
Age (years)	**Number of panels**	**No scaling**	**Slight/ moderate scaling**	**Severe scaling**	**Tons mined/month (thousands)**
0 – 1	5	3	1	1	260
1 – 3	3	2	1	-	110
3 – 10	2	2	-	-	50
+ 10	5	-	3	2	160
Total	**15**	**7**	**5**	**3**	**580**

Table 0–3 Condition of pillars related to safety factors

		Condition of pillars			
Safety factor	**Number of panels**	**No scaling**	**Slight/ moderate scaling**	**Severe scaling**	**Tons mined/month (thousands)**
1.0 – 1.5	2	-	1	1	90
1.5 – 2.0	3	-	1	2	170
2.0 – 2.5	4	2	2	-	270
+ 2.5	6	5	1	-	60
Total	**15**	**7**	**5**	**3**	**590**

1.12 List of sites visited

Table 0–4 lists the mines visited and shows the status of the checklists.

Table 0–4 List of mines and status of checklists

Mines visited	Resp. Person	Checklist completed
Gloria	Jan du Plessis Piet van Vuuren	Yes
Blinkpan	Jan du Plessis Piet van Vuuren	Yes
DNC	Dave Hardman	Yes
Tshikondeni	Jan du Plessis	Outstanding
Greenside	Dave Hardman Gavin Lind	Yes
New Clydesdale	Dave Hardman Gavin Lind	Yes
ZAC	Conri Moolman	Yes
Tavistock	Dave Hardman	Yes
Boschman's Section	Dave Hardman Gavin Lind	Yes
New Denmark	Jan du Plessis	Yes
Twistdraai	Jan du Plessis	Yes

1.13 Purpose of site visits

The purpose of the site visits was to:

- validate findings from previous research
- identify current practices
- evaluate probable methods for future reference.

Pillar extraction is undertaken in order to increase the amount of coal recovered from a given in situ resource. It may be done to extend the life of a mine, in order to continue supplying customers with a particular quality of coal, or to maintain production at a particular level when existing development panels have encountered poor mining conditions and there is a sudden shortage of 'pit room'. Whatever the reason for adopting pillar extraction, it must be done safely and profitably with a minimum amount of disturbance to the environment.

As part of the Coaltech project, an evaluation of the current practices was required. For this purpose a checklist was developed, a copy of which is given in Appendix 4.

In the checklist an attempt is made to elicit a quantification of the various constraints. The information required can be summarised as:

- General information
- Extraction method
- Extraction sequence
- Extraction equipment
- Production rates
- Personnel employed
- Original design parameters
- Current pillar conditions and measurements
- Roof and support conditions
- Additional information
- Problems experienced with pillar extraction and solutions, if possible
- Age of pillars
- Quality
- Surface
- Underground
- Costs/revenue
- Engineering
- Safety and health
- General
- Detailed survey of the panel
- Borehole logs
- Detailed geotechnical information (slips, joints, faults, dykes, multiple seams, etc.)
- Surface information and restrictions
- Mining history (previously extracted panels).

1.14 Conclusions from site visits

Although the database was small and consequently the correlation low, the following conclusions can nevertheless be drawn:

a) The initial safety factor of the pillars has a major effect on the pillar conditions during pillar extraction, specifically near the stooping line.

b) The pillar conditions at the stooping line tend to deteriorate more rapidly as the age of the pillars being extracted increases.

c) Mine personnel working with pillar-extraction panels do not perceive the age of the workings as contributing to the hazard of pillar extraction.

d) About 40 per cent of the tonnage mined at the time had been produced from panels older than three years or with a safety factor of less than 2.0.

From the discussions with and site visits to various mining groups, it became apparent that the following mining groups practised total pillar extraction (the mines associated with this practice are also listed below):

a) Iscor: DNC
Tshikondeni

b) Sasol: Twistdraai
Sigma

c) Duiker: Tavistock
Boschman's Section.

It was further observed that except for the Tshikondeni Colliery and the Sasol mines, all the mines were mining previously developed sections whose panels were not originally designed for total extraction mining methods.

It was also apparent that the mining method employed, and especially the pillar mining sequence, was site-specific. As such, the design and the mining methods used were specifically adapted to suit local mining and geological conditions.

In all the feedback received it was claimed that this method of mining was as safe as or even safer than normal bord-and-pillar development. These findings are similar to those reported by Oberholzer *et al*. (1997).

It was further evident that extraction efficiency (of single pillars) is site and operator-specific. The final extraction efficiency is normally a matter of judgement on the part of the operator.

There was no difference in coal quality except in panels where high levels of oxidation were reported.

It was reported by the mines that the cost of later pillar extraction is generally lower than the development cost when pillar extraction follows directly after pillar development. This aspect was not further investigated but it was determined that no provision was made for unforeseen costs such as major roof collapses. This lower cost is most probably the result of lower support requirements during secondary extraction. However, where extensive clean–up of old panels has to be done along with the provision of extensive additional roof support and the installation of support services, the cost of pillar extraction increases.

There are two distinct different approaches to the ventilation of goafed areas in this mining operation. The primary ventilation is normally directed over the continuous miner into the back or goafed area. The goaf is then either ventilated into bleeder roads or coursed into return airways.

A qualitative and quantitative approach to site inspections prior to the opening of an old mined-out bord-and-pillar section is critical. It was generally felt that detailed decision-making about the method to be employed was only possible after a thorough in-section evaluation of the reserves available and the prevailing mining and panel conditions had been done.

Review of current mining practices

1.15 Introduction

A checklist (Appendix 4) was compiled to collect information from collieries that had previously, or were presently practising pillar extraction using continuous miners or roadheaders. Since the target coal regions of the Coaltech research is the Witbank Coalfield and the Highveld Coalfields, those collieries within or adjacent to this Coalfield have been reviewed although information was collected from more distant Coalfields.

The ten collieries from which checklists were obtained are as follows:

Greenside Colliery, Anglo Coal
New Clydesdale Colliery, Anglo Coal
Boschman's Colliery, Duiker Mining
Arthur Taylor Colliery, Duiker Mining
Koornfontein Colliery, Gloria Shaft, Ingwe
Koornfontein Colliery, Blinkpan Shaft, Ingwe
Twistdraai Colliery, Sasol Coal
New Denmark Colliery,Anglo Coal
Durban Navigation Collieries, Iscor
Zululand Anthracite Collieries, Ingwe

For completeness the data for Durban Navigation Collieries (DNC) and Zululand Anthracite Colliery (ZAC) has been included in the tabulations although it is realised that factors at these sites may not be pertinent to the Witbank Coalfield region. In the case of DNC, the greater depth of around 250 m and large pillar size of about 25 m square pillars far exceeds what is to be expected in the Witbank Coalfield. Conditions at ZAC in the Zululand Coalfield are also considered not to be representative of the Witbank region. Although the data from these two collieries are included in the tabulations, reference to them will be minimal in comparison to the other eight collieries. Data for New Denmark Colliery has been included but this concerns the application of shortwall equipment to take out a limited number of old pillars at a depth of 200 m and at a mining height of about 1.8 m.

Appendix 1 compares the geometry of the sites from which pillar extraction data was obtained along with the resources used (equipment and men) and the outputs obtained.

Appendix 2 compares the geology and support performance/efficiency and Appendix 3 lists some of the problems associated with the pillar extraction panels together with financial, engineering and safety performance in comparison to bord and pillar development panels.

Checklist information covers the use of ‘full’ pillar extraction allowing the goaf to cave, partial extraction of pillars leaving small snooks to support the goaf on a temporary basis and checker-board extraction where alternate pillars are left to support the goaf area. In the latter situation, mines have designed the panels so that the remaining pillars after checker-board extraction, will not fail violently but will yield over time. Partial pillar extraction has the advantage of not creating a goaf edge that requires breaker line support and also can preserve the water table. Proponents of partial pillar extraction claim that resource recovery can be as effective, if not better, than ‘full’ pillar extraction.

1.16 Range of geometrical and geological settings

Three of the checklists cover pillar extraction in the No 2 Seam of the Witbank and Highveld Coalfields, four from the No 4 Seam and one from the No 5 Seam. For the 4-Seam workings, the extraction height ranged between 1.8 m and 3.8 m while that in the No 2 Seam ranged from 3.6 m to 5 m. The extraction height in the No 2 and 4 Seams was sometimes less than the Seam height, thereby leaving coal in the roof. The No 5 Seam pillar extraction operation took the full Seam height of 1.8 m as did the shortwall operation at New Denmark.

Pillar width varied between 18 m and 8.5 m, depth varied between 200 m and 30 m and the bord width ranged between 6.5 m and 7.5 m. Safety factors were generally within the range of 1.7 to 2.1.

Panel widths ranged from about 120 m to 210 m for the bord and pillar operations which, when compared to the depths of the panels, results in a width/depth ratio variation from over 6 to just less than 1. Apart from the shortwall at New Denmark colliery, all pillar extraction operations made use of either a drum-type continuous miner or a roadheader. Output per month varied between 19 000 ton in a low Seam height operation and 50 000 ton in a thick Seam operation and output per man per month varied between 1 055 ton to 4 167 ton.

1.17 Geology and support effectiveness

Of the ten different collieries, only DNC has a significant thickness of dolerite in the superincumbent strata which could limit the extent of caving.

The immediate roof strata is typical of local coal seams, being mainly sandstone, although some shale or shaley-sandstone is also reported. Where a mine does not take the full seam thickness, generally for quality control reasons, the immediate roof becomes coal. Floor strata is generally sandstone although some occurrence of shale, shaley-sandstone and siltstone is also reported for some mines.

Length of installed roofbolts ranges between 0.5 to 1.9 m, with 1.2 and 1.5 m long bolts being the most favoured. In some cases, 5 m long cable anchors are also used to support specific areas by some of the mines. Generally, roof competence is reported to be good to excellent by most of the mines except in the vicinity of slips and faults. The majority of mines do not have problems with support failures and current support conditions are reported to be good. Similarly, pillar punching into the floor is not foreseen as a problem neither is pillar fracturing, except at the two KwaZulu-Natal collieries.

From personal visits to pillar extraction sites, the main support problem area is the intersections, particularly adjacent to the pillar being extracted in a ‘full’ extraction panel. That is to say in a region of high stress. There is also a high risk of sidewall collapses. It is at this intersection where continuous miners are most likely to be buried by a fall of roof.

Bord widths are quoted above to vary between 6.5 m and 7.5 m and, although these widths may be stable in bord and pillar development panels, the additional induced stress from pillar extraction can result in intersection collapse. This will be made worse where old panels are being extracted and pillar spalling may have caused an increase in bord widths, particularly if the panels were originally formed by drill and blast methods.

1.18 Surface and underground environmental concerns

Where mines are practising ‘full’ pillar extraction, surface subsidence occurs to an amount reported to be from about 33 per cent of the extracted seam height at New Clydesdale Colliery to almost 80 per cent at Boschman’s Colliery. In the case of those collieries applying a checker-board pillar recovery method surface subsidence is either minimal or does not occur at all. There are some inconsistencies with regard to the effect of pillar extraction on the water table. It is to be expected that where mines are practising ‘full’ pillar extraction and experiencing subsidence then this would also affect the water table. Conversely, where the checker-board method is in use and caving of the upper strata is absent then the water table should remain generally unaffected. This is not always the case as reported by the mines. In these cases, the height at which the groundwater table occurs in comparison to coal horizon and mining thickness play a significant role.

Of the ten mines, only one, DNC, reported spontaneous combustion to be a problem and only three mines, DNC, Twistdraai and New Denmark reported methane to be a problem. Twistdraai, New Denmark and Boschman’s Collieries reported problems with airflow through and over the goaf.

1.19 Variation in coal quality and size

Only two collieries, Twistdraai and New Denmark, reported that there was a change in the coal quality. For Twistdraai it was indicated that there was less contamination but the cause for this is not stated. (It was found in many cases of “full” pillar extraction, that people tend to leave coal in the roof and floor to increase speed of extraction.) The opposite occurred at New Denmark where contamination from cutting in the floor resulted in an increase in stone in the run-of-mine product.

Most of the mines report a larger product size during pillar recovery operations but only one mine, Gloria shaft, quantified the increase as a 5 per cent increase in larger coal. The increase in coal size is also supported by other remarks that some mines make with regard to easier cutting conditions and lower pick costs (more tons per pick). All of these factors support a more efficient cutting process during pillar recovery in comparison to pillar development.

1.20 Machine efficiency and machine modifications

The majority of the mines report no difference in machine availability during pillar recovery operations compared to pillar development. However, DNC report lower availability and Greenside and NCC report better availability. In the case of DNC reduced availability is due to delays caused in repairing machines after being damaged by roof collapses. For Greenside and NCC better availability is reported to be due to more attention being given to machine maintenance and repair because of the need to remove pillars quickly with as little delay as possible.

Most mines make some machine modifications in order to better facilitate pillar recovery. Modifications include:

- removal of the dust scrubber in case it gets damaged in a roof collapse,
- provision of protective cage and high speed tram on shuttle cars,
- provision of cable arm and automatic reverse on the continuous miner,
- modification to continuous miner traction motors so that they can be operated via a shuttle car cable in case of damage to the continuous miner cable.

1.21 Section safety

Contrary to historical beliefs, all mines report no difference in safety performance in pillar recovery sections when compared to pillar development sections. Two mines quote a better safety record in pillar recovery sections due to a greater awareness by the employees of the need to be alert at all times. No statistical results are available to confirm this finding, but the checklist answers were compiled/provided by mine managers or section managers from their own knowledge of pillar extraction practice.

1.22 Costs

It is realised that mines do costing in different ways and some costs quoted by some of the mines cannot be directly compared to each other. However, all mines except Boschman's Colliery and New Denmark Colliery, report that pillar recovery operations are cheaper than pillar development operations. The reasons given for this are lower pick costs (easier cutting) and lower support costs. Boschman's Colliery report a higher cost for pillar recovery because of the additional cost of rehabilitating the old panel in terms of re-supporting, cleaning up and re-stone dusting. New Denmark's higher cost per ton when removing pillars, as opposed to conventional shortwall, is due to a reduced tonnage of coal per metre run of face length because of the presence of roadways.

1.23 Method of pillar removal

A comprehensive literature survey, questionnaires sent to Industry and numerous site visits both to local and international mining operations confirmed the application of only old, known methods of pillar extraction.

Various variations of these methods are however practiced with great success.

The most recent development in the field of pillar extraction identified during the research is the so-called Nevid-method developed by Sasol Coal and practiced extensively with great success. This method resembles a method practices by Ermelo Mines Services during 1984 in the extraction of small pillars (± 9.5 m pillars). The general trend in pillar extraction with continuous miners has moved completely away from the traditional 45 ° stooping line to a 90 ° stooping line.

A number of subsequent industry workshops also did not produce any new innovative ideas for further development.

The various successful methods used or approaches to pillar extraction can be grouped into three distinct categories based on current application:

- **Small to medium pillars (angled cuts)**

This method entails a number of almost diagonal cuts through the pillar from the safety of two solid pillars. Small snooks are left on the outside of the pillar with a reasonably large snook or “rib” protecting the intersection from where the cuts are taken. Boschman’s Colliery and Auther Taylor Colliery are using this method successfully on pillars from approximately 10 m up.

- **Medium to large pillars (split and fender)**

Methods in this category stems primarily from the development of the rib pillar extraction method. In this method, normal predeveloped pillars, both square and rectangular, are split in ribs by cutting through them at right angles. The ribs are then mined with a series of angled cuts similar to the rib pillar extraction methods.

Collieries such as Sigma, Brandspruit, Middelbult, Twistdraai, Bosjesspruit, Longridge, Springfield and DNC have successfully applied this approach in pillars from 18 m and larger. Currently Middelbult Colliery is still applying this method.

- **Medium to large pillars (angled cuts)**

Sasol Coal developed the so-called Nevid method at its Bosjesspruit Colliery for pillar extraction in horizontally stressed environments. The method is based on carefully planned angled cuts from two directions through the pillar, leaving snooks on the outside. A strong final rib is left protecting the intersection from which mining takes place.

Currently Brandspruit, Twistdraai and Bosjesspruit Collieries are practising this method with overwhelming success on pillars from 24 m upwards.

1.23.1 Small to medium pillars (angled cut method)

Introduction

A number of collieries has in the past experimented with, and applied pillar, extraction on small pillar ranging from 9.5 m upwards. These include Longridge, Ermelo Mines, Greenside and Sigma. The overall approach was to take a number of diagonal cuts through the pillar. In all of them, either the first or the last cut attempted to remove the diagonal rib (left from the intersection from where cutting takes place. The focus appeared to be maximum recovery of the pillar rather than controlled goafing and intersection stability.

Both Boschman’s Colliery and Auther Taylor Colliery are currently practising a similar approach to pillar extraction with the exception that the critical intersection is supported by means of a predetermined rib or snook along the diagonal. Pillar extraction has been practised as shallow as 30 m and at safety factors as low as 1.6. The method is applied on pillars of 4 to 5 years old, developed through conventional drilling and blasting methods.

Production rates of approximately 50,000 tons per month are achieved with this method.

Mining method and cutting sequence

Contrary to the traditional way of pillar extraction (1980's), pillars are extracted in a straight line and not on a 45° stooping line. The standard practice is to extract pillars from left to right but it has been done successfully the other way round as well. Typical 9 – road sections developed by drill and blast methods 4 to 5 years ago are mined successfully with this method. All pillars, including the barrier pillar between adjoining panels are removed.

Three single cuts are taken through the pillar as depicted in Figure 0–1 (b). This ensures always mining away from the goafed area as well as the safe positioning of the continuous miner operator and cable handler.

The angled cuts through the pillar eases continuous miner movement and allow for rapid retreat should goafing threatens. The ease of cutting also provides for consistent snook sizes, depending on pillar geometry.

Strata control and roof support

At Boschman's Colliery, the whole panel requires re-supporting as the original roofbolts have been installed and tensioned by hand. These bolts were 0.7 m mechanical anchor bolts. The new support consists of 1.5 m point anchor resin bolts spaced at 2 bolts per row every 2 m.

Roofbolt breaker lines are used throughout as indicated in Figure 0–1 (a) and consists of 1.2 m point anchor resin bolts spaced 1 m apart in the row and rows 1 m apart. A timber prop (policeman) is installed as indicated on completion of cut No 2 for early warning of roof movement. Two-timer props per roofbolt breaker line are also installed as a policemen.

A diagonal rib starting 1 m on either side of the corner from where cutting is done is left to protect the intersection. This is critical in ensuring maximum protection of the continuous miner during and until after cut No 3. The rib thins out towards the goaf side to increase percentage extraction and to ensure proper goafing which, in shallow workings can cause serious problems.

No mobile breaker line supports are used. A continuous miner extractor is provided to ensure quick retrieval of the continuous miner should the situation warrants.

At shallow depths of down to 30 m, surface subsidence is quite severe and causes major cracks and undulations on surface. Future pillar extraction at Boschman’s will consequently be limited to depth below surface of 50 m and more. All pillars including the barrier pillars are removed in order to increase overall extraction and to obtain smother surface subsidence profile.

Ventilation

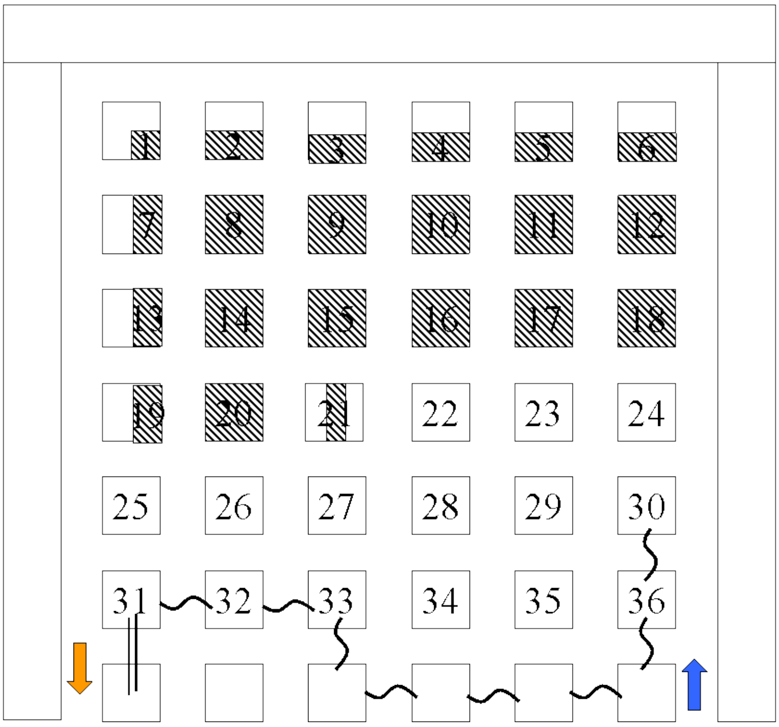
Ventilation is coursed through the section from right to left by means of line brattices as depicted in Figure 0–1 (a). A jet-fan is used in the last through road to assist in the coursing of the ventilation.

The small pillars and resulting short cutting distances result in excellent ventilation as well as low dust levels.

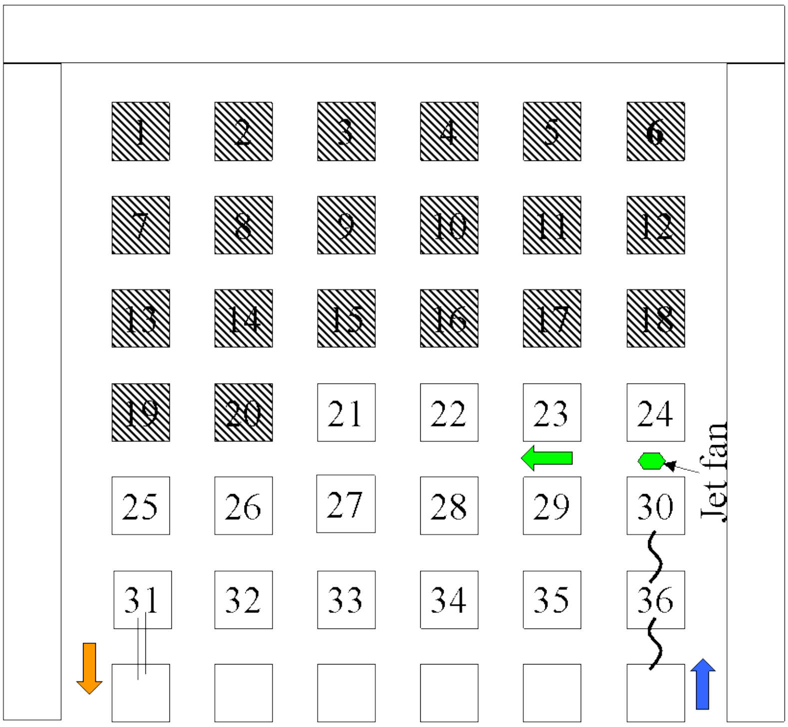
No bleeder roads are left, as the occurrence of methane is very low.

Percentage extraction

On typical 10 m pillars, the theoretical percentage extraction amounts to ± 75 per cent, resulting in an overall extraction of 85 per cent should barrier pillars be left and 90 per cent where barrier pillars are also extracted.



(a)



(b)

Figure 0–1 (a) Extraction of medium to large pillars with split and fender method - mining sequence and ventilation layout with half bleeder road (b) Extraction of small pillars with angled cut method - mining sequence and ventilation layout with no bleeder road

1.23.2 Medium to large pillars (split and fender method)

Introduction

This method has developed over a number of years from optimisation of the typical rib-pillar extraction methods. One of the major problems with rib-pillar extraction is related to the varying production rate. Production during the initial development stage (2 and 3 road development) as well as with the development of the ribs is relatively low. This is a result of long tramming, shuttle car change-out time, limited tramming roads and the cutting/roofbolting interaction. During the extraction of the rib (fender) production is higher, but still constrained by long and limited shuttle car tramming roads.

Various collieries have been involved in the development of this method over a number of years. The common principle is the splitting of a pillar into 2 to 3 fenders (ribs) which are extracted similar to rib-pillar mining.

Production rates of approximately 60,000 tons per month are achieved with this method.

Mining method and cutting sequence

In this method, panels are developed with 7 to 9 roads at pillar centres of 24 m and more, resulting in pillar sizes of approximately 18 m. Pillar geometry, in terms of being able to be split into fenders (ribs) of approximately 6 m, is the main criterion for pillar design, provided the safety factor does not go below 1.6. Square pillars are common practice, although rectangular pillars have also been successfully mined.

Pillar centres must preferably be multiples of 12 to 14 m in at least on direction to allow for fenders of approximately 6 m after splitting of the pillar.

Once the end of a panel is reached, pillar extraction commences, with pillars being extracted from left to right in a straight line, as depicted in Figure 0–2 (a).

Pillars are normally split lengthwise in the direction of the panel, leaving 2 to 3 fenders of approximately 6 m as depicted in Figure 0–2 (b).

Once the fenders are created, they are extracted by taking a number of angled cuts through them as depicted in Figure 0–2 (b), similar to rib-pillar mining. This cutting sequence is ideally suited to remote controlled continuous miners as it affords the continuous miner operator maximum visibility of the continuous miner from a safe location i.e. protected by solid pillars.

Strata control and roof support

During pillar extraction roofbolt breaker lines are installed as depicted in Figure 0–2 (b) consisting of a double row of resin bolts spaced at 1 m intervals.

During the splitting of the pillars into fenders, it is important to keep the split as narrow as possible, without inhibiting the manoeuvrability of the continuous miner when extracting the fenders. No roofbolts are installed in the split, provided the maximum distance cut does not exceed the mine Code of Practice for Roof support requirements and both shuttlecars and continuous miners (except remote controlled continuous miners) are equipped with adequately design canopies.

The split must also be at 90 ° to ensure fenders of consistent dimensions.

If not cut at 90 ° it may result in poor roof control and inconsistent snooks (too large) left especially on the wide end of the fender. This may result in goafing problems.

A large snook is left of each fender closest to the intersection from where pillar extraction is done to provide maximum protection to that intersection. Attempts to extract this last snook have resulted in many continuous miners being buried in the goaf.

Mobile breaker line supports were developed and used at Sasol Coal many years ago. The use of these was discontinued due to their tendency to get stuck in the goaf as well as other logistical problems. The development of roobolt breaker lines as currently practised at most pillar extraction operations, resulted in a much smoother and more productive pillar extraction operation.

Ventilation

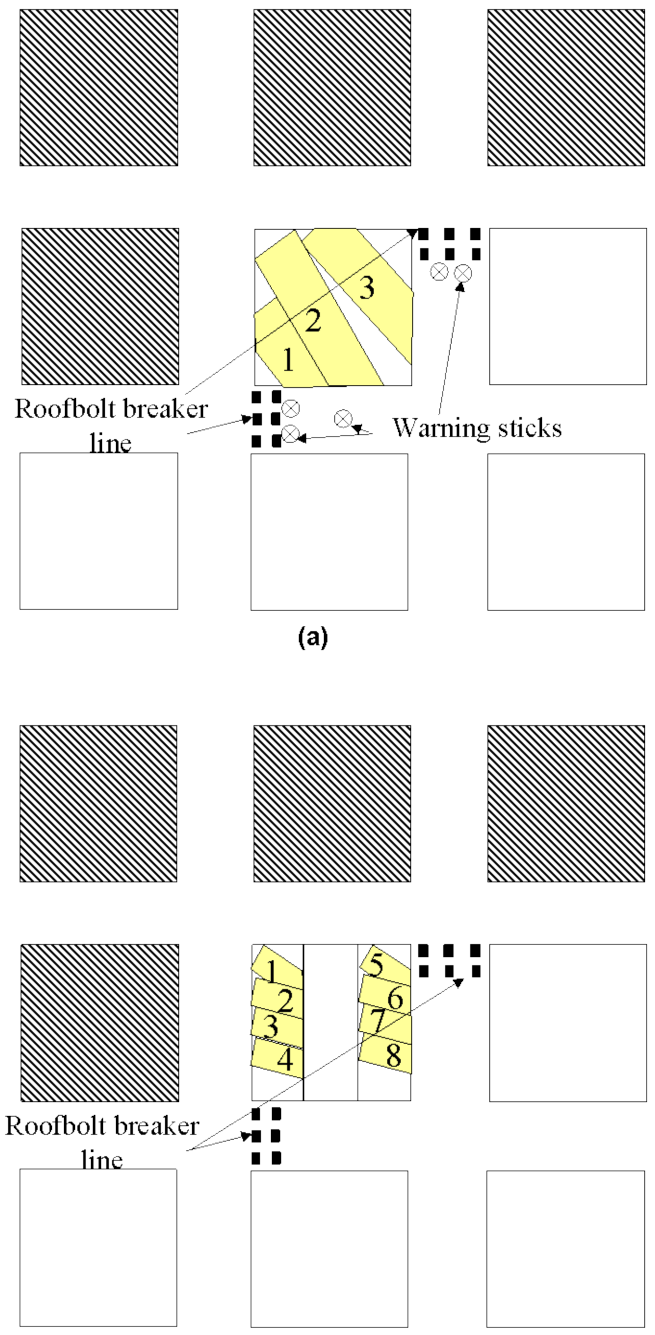
The ventilation is coursed through the section from right to left as depicted in Figure 0–2 (a).

During the splitting of the pillar either a jet-fan or a line brattice is required to ventilate the heading and remove gas and dust, as the cut is generally driven more than 10 m past the last through road.

Depending on the methane liberation properties of the coal seam and the overlying strata, the establishment and maintenance of a bleeder road on one side of or fully around the panel/panels to be extracted is required. Various incidents of methane ignitions have already occurred at the goaf edge or inside the goaf.

Percentage extraction

On typical 18 m pillars, the percentage extraction amounts to 60 per cent of each individual pillar. This is primarily the result of spillage from the continuous miner into previous cuts, inconsistent snook sizes and the size of the final snook left to protect the intersection. Overall extraction varies from a low of 66 per cent at 100 m below surface, if barrier pillars are left intact and a full bleeder road is required around each individual panel, to approximately 80 per cent if barrier pillars are mined and bleeder roads are not required.



(a)

(b)

Figure 0–2 (a) Extraction of small pillars with angled cuts - cutting sequence (b) Extraction of medium to large pillars with split and fender method - cutting sequence

1.23.3 Medium to large pillars (Nevid method)

Introduction

Sasol Coal developed the Nevid method of pillar extraction at their Bosjesspruit Colliery to overcome the majority of problems experienced with other pillar extraction methods in horizontally stressed areas. The Nevid method of pillar extraction can be classified as a partial pillar extraction method. In fact, virtually all pillar extraction methods are partial pillar extraction methods as snooks of varying shapes and sizes are left behind to protect people and equipment and to control the goafing of the immediate roof.

The name “Nevid” originated from the names of the two people responsible for the development of the method, i.e. Neels Joubert and David Postma at Sasol Coal. The method is fairly adaptable and can be applied in virtually all circumstances.

Various problems are continuously encountered with the conventional approach to pillar extraction. These are primarily resulting from horizontal stresses and the inconsistency of snooks left behind in the goaf area. The latter is caused by the difficulty of cutting at right angles to existing roadways or new lifts taken. The number of lifts taken and the direction in which they are taken are to a large extend left at the discretion of the continuous miner operator and section miner.

Specific problems resulting from the above include: -

- poor ventilation
- massive and unpredictable goaf behavior
- burial of continuous miners
- accidents
- airblasts resulting in damage to ventilation structures and injuries
- variable and unquantifiable extraction of reserves
- people exposed to unsupported roof and
- variable production rates.

The Nevid method was developed to overcome most of these problems through easy control over cutting sequence and specifically cutting direction

The typical layout for the Nevid method of pillar extraction provides for a 7-road layout with 28 meter center distances, although centers can be reduced to 24 meters with the same pillar extraction cutting sequence as depicted in annexure 3.

Mining method and cutting sequence in Nevid method

At the start of a new panel, which is after completion of the panel development, the top middle pillars are split as depicted in Figure 0–3 in order to increase overall extraction of the coal. They are not mined fully to prevent the goaf from running into the ventilation bleeder road around the panel. Two double lifts are cut through the pillar in the top right corner similar to the cutting of all pillars next to the right barrier. These pillars with only two lifts cut are left to establish the rest of the bleeder road around the panel.

Cutting then follows he sequence as depicted in Figure 0–3, starting from left and always working to the right. All cuts are taken a 45-degree angle to the centerline of the original development. Cutting direction lines are in all cases installed on the roof on the right-hand side of the first lift (“a”-cut) to be made by the continuous miner as depicted in Figure 0–5. This ensures that the continuous miner operator can always easily control the cutting direction from a safe position. The “a” lift is always cut before the “b” lift. As the “a” lift is always shorter than the “b” lift, it ensures breaking through into the return air side of the pillar in the shortest possible time. This establishes through ventilation and improves dust removal and methane drainage. The “b” lift is always taken right up against the most solid side of the remaining portion of the pillar being mined. This ensures maximum protection to the continuous miner.

Strata control in Nevid method

The primary success of the Nevid method stems from two specific aspects: -

-The specific cutting sequence and
-The consistency of snooks left.

The cutting sequence of each individual pillar as well as the extraction sequence of subsequent pillars affords maximum protection to the continuous miner at all times. The continuous miner always has a solid pillar or the strongest possible remaining snook adjacent to it. The 45 degree cutting angle also provides for the fastest possible retreat of the continuous miner should goafing conditions requires such action.

Each individual pillar is marked off in terms of cutting position and cutting direction lines prior to any cutting according to a predetermined pillar design. The 45 degree cutting angle allows for much easier cutting and direction control. It further improves the vision from the continuous miner operator for better control of the continuous without exposing him to high risk areas. Strict adherence to this layout ensures consistency of snooks left behind. This provides for a fairly consistent and almost predictable goafing pattern.

The goafing generally follows the extraction of pillars by one row of pillars. The consistency and size of the snooks ensure a steady and moderate goafing behind mining. Should the goaf however hang up for more than two rows of pillars, a stopper pillar is left on the third row as depicted in Figure 0–3. This is done to counter violent goafs and reduce the risks of potential air blasts. Each goafing situation is evaluated individually and no stopper pillars are left in the event of no hanging up of the goaf.

In the event of mining on the weak side of joints, great care must be taken. This includes the cutting of single lifts or even no cutting at all.

Critical dimensions for the positioning of the various cuts are indicated in Figure 0–5 for a typical 28 meter center pillar layout. This plays a critical role in the strength of the remaining snooks and subsequent goaf development and is essential to the success of this method. Different pillar sizes may require different distances and even possible variation in the taking of single or multiple lifts through the pillars.

Roofbolt breaker lines are used throughout as they allow ease of installation, may for part of the initial systematic roofbolting during development and are provided at low cost. They have further proved to provide sufficient support for various pillar extraction methods in South Africa. Roofbolt breaker lines are installed in all positions as demarcated in Figure 0–5.

Warning sticks or “policemen” are installed in the positions as shown in Figure 0–5. Installation of warning sticks must be completed prior to commencing with cutting on the adjacent “a” cut. These are required as early warning device for any potential snook failure and/or roof movement.

Ventilation in Nevid method

Two critical ventilation aspects require attention in all types of pillar extraction, both of which are better addressed in the Nevid method than in other methods. These are; bleeding methane out of the goaf, and taking dust and possibly methane away from the working area. This provides for a much healthier and safer working environment.

The general ventilation layout is such that most intake air is coursed directly over and/or behind the continuous miner straight into the mined out zone. From there it goes directly into the return airway, which is also the bleeder road. This ensures that both methane and coal dust are continuously taken away from the people and working area directly into the return airway. During all cutting the continuous miner operator is positioned on the intake side of the continuous miner and not exposed to any dust. It is only during the first lifts, marked “a”, in Figure 0–5 that the continuous miner is not cutting in through ventilation in the sense that air is moving past the continuous miner instead of directly over it as in the “b” lift. This is however always the shortest lift and results in the quickest holing through into the mined out zone and establishing through ventilation.

After completion of cut 1, a ventilation curtain is installed in position “A” as indicated on Figure 0–4. This ensures maximum ventilation flow past cut 2. On completion of cut 2, the curtain at position “B” is removed and installed in position “C” before cutting 3 and 4. After completion of cut 4, the curtain at position “C” is removed and installed at position “D”. This cycle is repeated until cut 14, after which the curtain at position “E” is moved to position “F” and the curtain at position “A” is removed.

Unlike most other pillar extraction methods, the last row of pillars extracted remains open up to the mining of the next row, which allows for proper ventilation throughout the cycle. This is to a large extent as a result of the design of the snooks left and the subsequent consistent goafing.

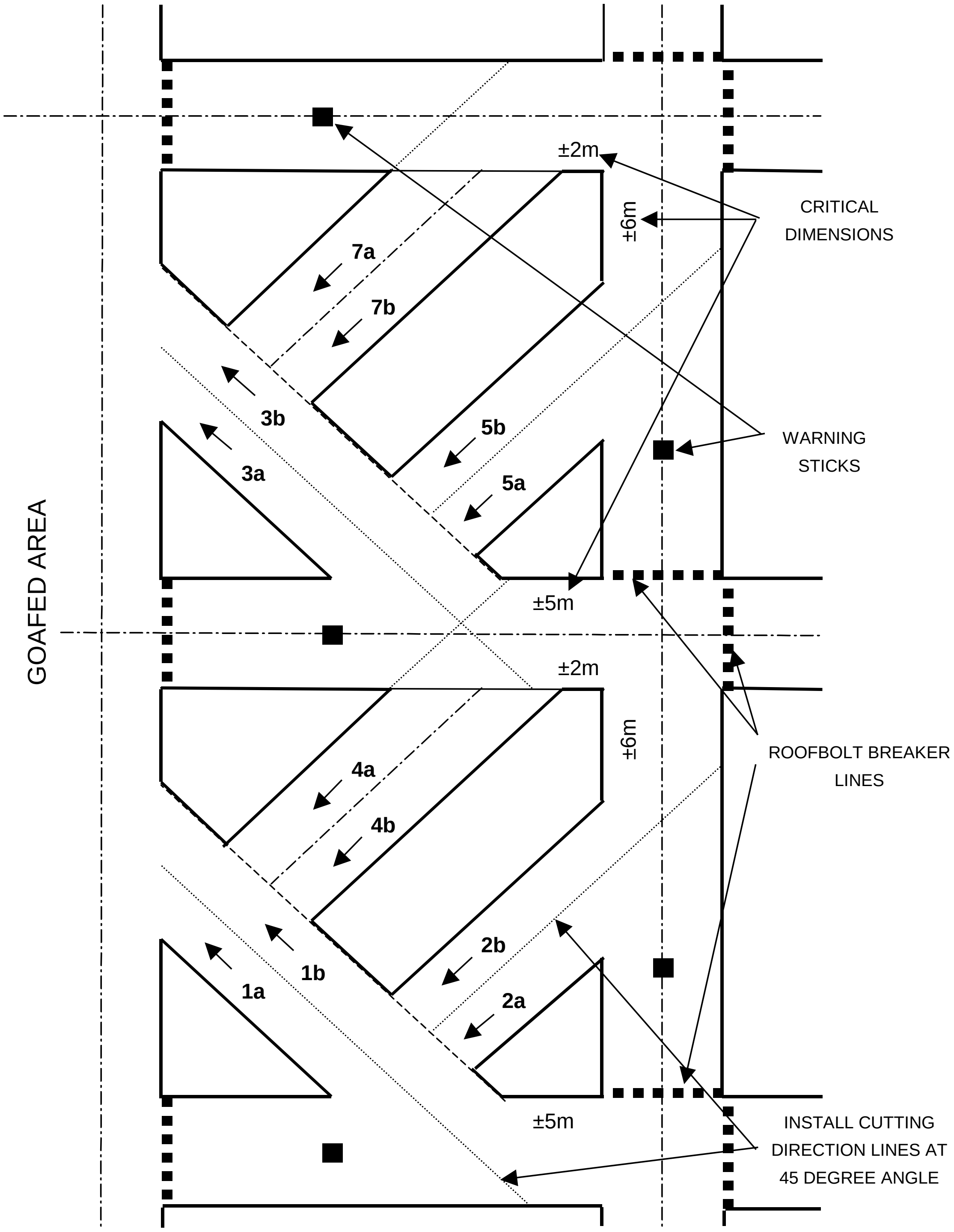


Figure 0–3 Nevid – pillar extraction cutting sequence

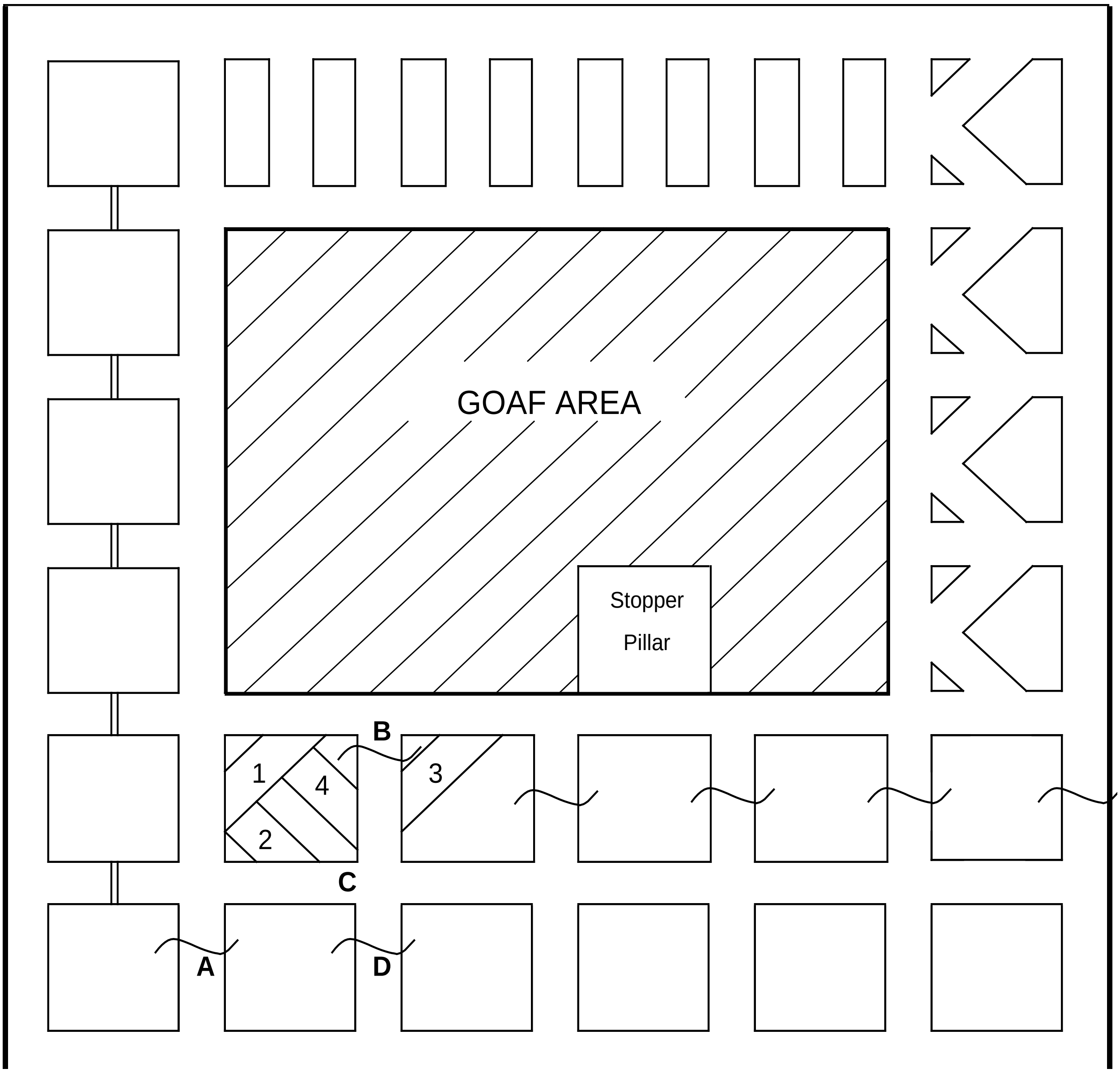


Figure 0–4 Nevid ventilation layout

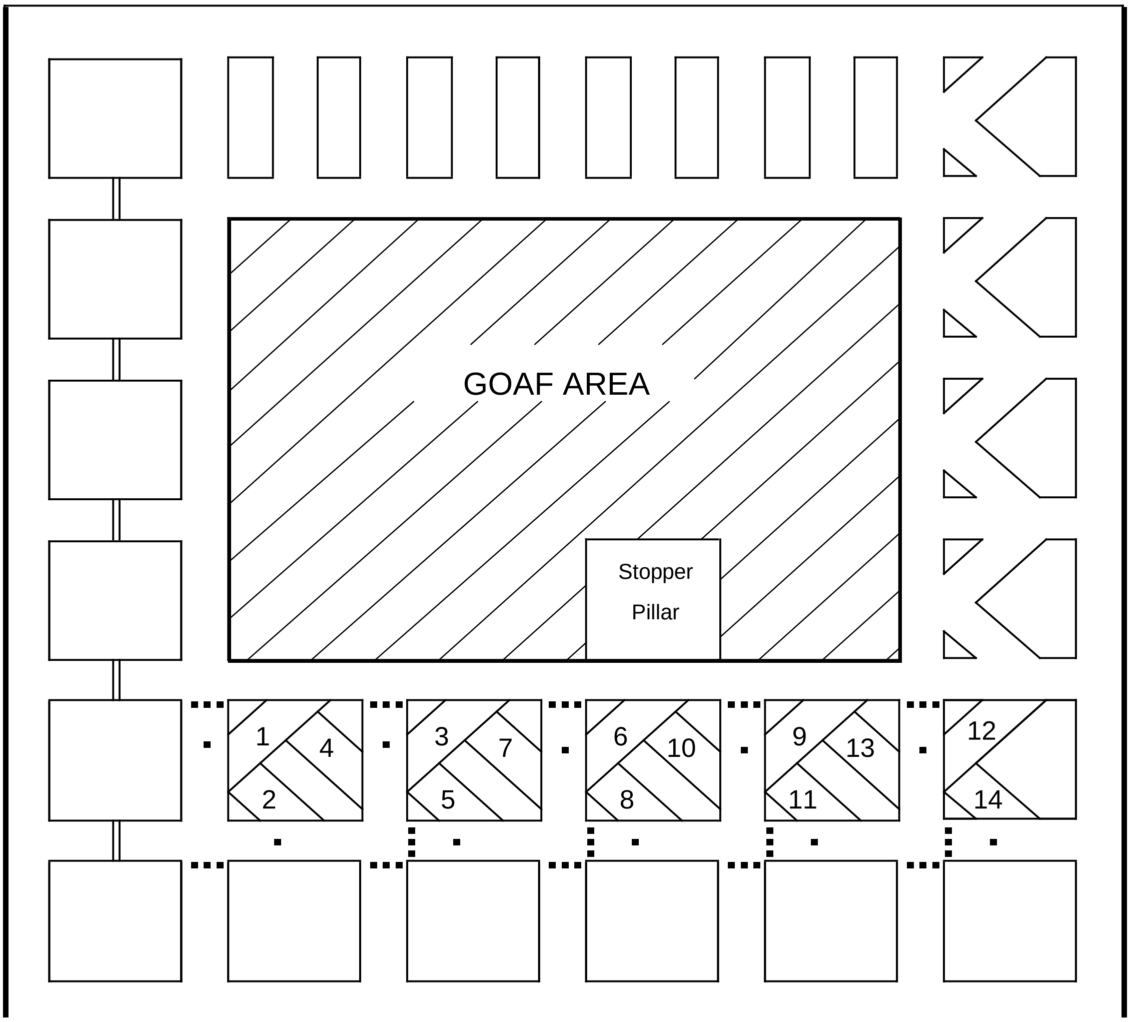


Figure 0–5 Nevid stooping cycle

1.23.4 Conclusions

Pillar extraction takes many forms and mines have adopted methods of removing individual pillars to suit their particular needs. In ‘traditional’ stooping, it was recommended practice to remove or destroy all snooks in order to allow the goaf to cave thereby relieving the stress on the caving pillar line. Many of the pillar extraction methods now used deliberately leave pre-designed snooks that prevent immediate caving but will crush over time. Advantages of these methods are:

- the absence of a caving line, thus removing an area of high risk,
- immediate water table disturbances, and
- elimination of the problems/dangers associated with goaf ‘hang-ups’ and sudden goaf collapses.

- Improved ventilation flows and methane drainage.

One major disadvantage of keeping up the goaf by the use of pre-designed snooks or by the use of checker-board mining is the uncertainty of when the snooks or remaining pillars are going to crush and allow the overburden strata to settle.

Contrary to previously held views, mines now do not believe that pillar extraction is a less safe method than pillar development. This may be because pillar extraction is now done by continuous miner, often by means of remote control, and also that the incorporation of section employees in more risk assessment procedures has introduced a greater awareness amongst the underground operators of the inherent dangers in pillar extraction. Also, more use is now made of ‘partial’ pillar recovery and checker-board systems where the formation of a goaf edge is prevented, thereby removing a hazardous area from the system.

The cost of pillar extraction in comparison to pillar development is reported to be higher by some mines but lower by others. Much depends on a mine’s costing procedures and whether pillar extraction follows directly after pillar development or whether old panels have to be rehabilitated.

Pillar extraction by means of shortwall equipment has been done successfully but a particular problem can be the rate of retreat through the pillars. Over a face length of say 90 m made up of 4 fifteen metre square pillars and 5 six metre wide bords, coal is present over only two thirds of the shortwall face length and the other third is ‘air’. Careful consideration must be given to the logistics of utilising what is considered to be a highly capital intensive method for the recovery of pillars.

The recovery of old pillars by underground pillar extraction has been shown to be feasible in the No 4 Seam and the No 2 Seam in the Witbank Coalfield. Experience is being gained which should be beneficial to the industry in the wider application of pillar extraction to other parts of the Coalfield where suitable reserves may be found.

Application of “Nevid” pillar extraction method at shallow depth

1.24 Introduction

The NEVID method is a way of stooping pillars commonly employed in SASOL coal mines. Although, it has been identified as one of the best methods in pillar extraction, current design specifications for the method are specific to depth below surface of approximately 150 m, due to pillar size requirements. Nevid method has been practiced at shallower depths with smaller pillar sizes, which indicated that it was not successful due to great size of snooks left behind, which did not fail and prevented the goaf taking place in the panel. This resulted in great distances of overhangs, which was a great danger to work force underground.

The aim of this investigation is to determine the optimal controlling dimensions and lift width for stooping at various depths.

1.25 Methodology

The basic NEVID sequence and controlling dimensions for a depth of 160 m are presented in Figure 0–1. Note that the three dimensions indicated and the width of the lifts completely control the geometry and area of the snooks. Also note that the lifts in the diagram are 3.6 m wide. Two lifts are cut (a and b), resulting in a total lift width of 7.2 m. To avoid confusion, “lift width” will refer to the total width of the cut (a + b).

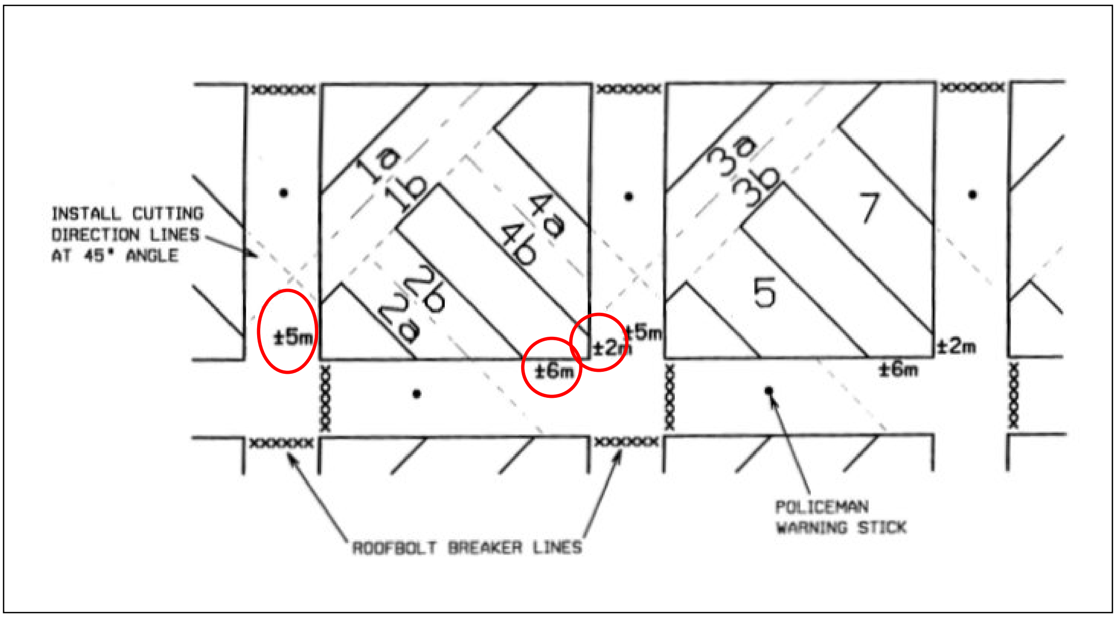


Figure 0–1 Controlling dimensions and cut sequence

The situation at 160 m depth is used as a reference solution for snook geometry. At this depth, the intact pillars have a safety factor of 2.0. The safety factor for the stooped pillars is calculated as follows:

The effective width of the stooped pillar is calculated using Wagner's (19) approximation:

$$w_{eff} = \frac{4A}{Q}$$

Where A is the total area of the snooks left from a single pillar and Q is the total circumference of the snooks. This effective width is used to calculate the strength of all the snooks using Salamon's formula:

$$Strength = \frac{7.12 w_{eff}^{0.46}}{h^{0.66}}$$

Where h is the seam thickness. The load on the pillar is calculated from tributary area theory:

$$Load = \frac{0.025 H C^2}{A}$$

Where H is the depth below surface and C is the centre-to-centre distance. The safety factor is then calculated as:

$$SF = \frac{Strength}{Load}$$

For the suggested NEVID geometry, the total snook area (A) is 140.9 m^2 and the total snook circumference (Q) is 96.7 m. This gives an effective pillar width of 5.83 m and a resultant safety factor of 0.35.

The calculated safety factor is used as a design criterion. The aim is now to determine the controlling dimensions and lift width for a variety of depths. Firstly, the pillar width for an intact safety factor of 2.0 is calculated using Salamon's formula with correction for continuous miner operation. The pillar widths for a safety factor of 2.0 is presented in Table 0–1.

Table 0–1 Pillar widths required for a SF of 2.0

Depth [m]	Pillar load [MPa]	Pillar strength [MPa]	Pillar width [m]
160	7.4	13.8	20.8
140	7.02	12.9	17.3
120	6.63	12.04	14.8
100	6.28	11.06	12.3
80	5.92	10.06	10

The controlling dimensions and snooks are labelled in Figure 0–2.

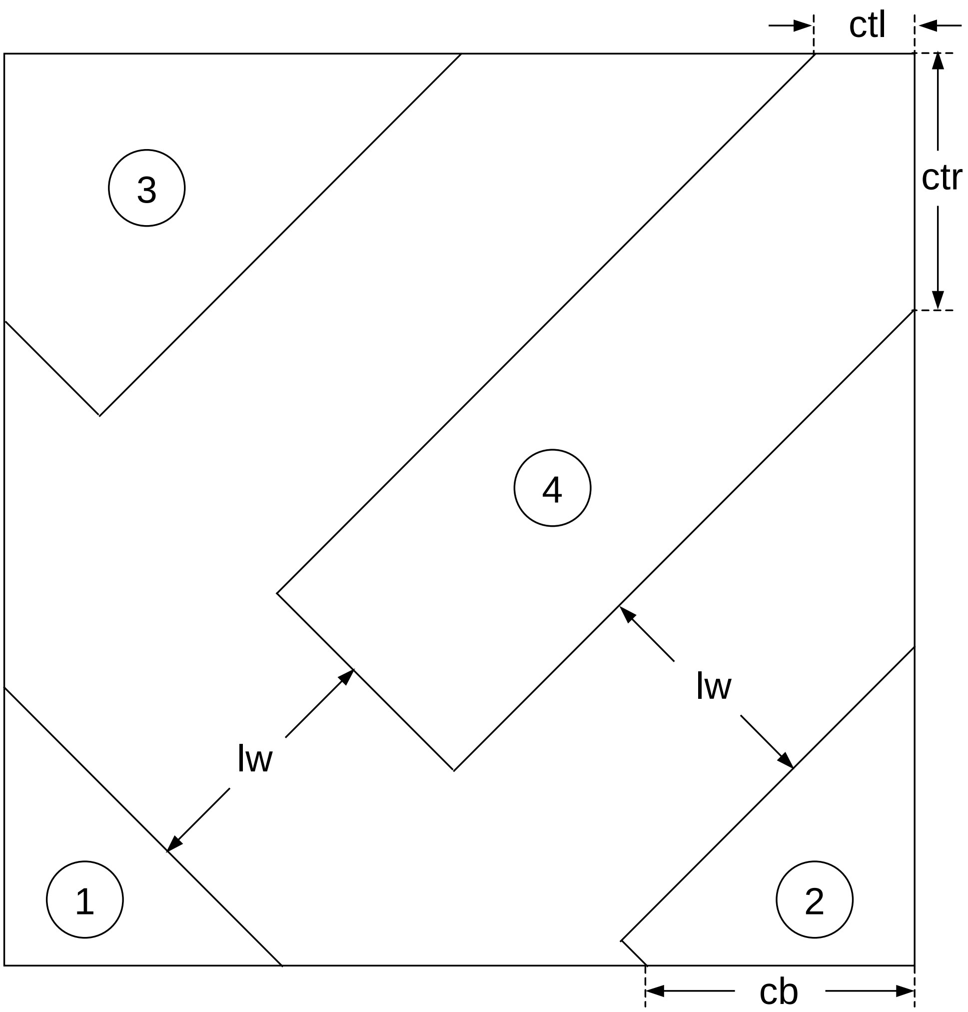


Figure 0–2 Geometry of Nevid method

The geometries and lift widths are varied for each depth until a stooped pillar safety factor of 0.35 is obtained.

1.26 Results

The extraction dimensions, lift widths and safety factors for NEVID pillars at various depths are presented in Table 0–2.

Table 0–2 Dimensions for stooping at various depths

Depth	ctr	ctl	cb	lw	A	Q	SF
160	6.0	2.0	5.0	7.2	140.9	96.7	0.35
140	5.0	3.0	5.0	6.0	107.5	84.6	0.37
120	4.0	2.0	4.0	5.0	78.7	77.1	0.36
100	3.0	2.5	3.0	4.5	53.0	59.1	0.35
80	2.4	2.4	2.5	3.6	36.0	47.5	0.35

Technical factors of constraint

1.27 Introduction

Pillar extraction, or stooping, has been practised for many years in South African collieries as a means of increasing the percentage extraction from in situ coal reserves. Over the years of its application, there have been many variations of the pillar-extraction method, some of which have proved more successful than others.

In pillar extraction, panels in a bord-and-pillar mining layout are used in which many pillars are created but only extracted at some later date as the panel must be developed completely before pillar extraction can commence. There are two basic approaches to pillar extraction. Firstly, the extraction of pillars in old workings where little or no account was taken of secondary extraction during the initial panel and pillar design, and secondly, the extraction of pillars in panels designed specifically for pillar extraction.

This report concentrates mainly on panels where the pillars were not originally designed to be extracted.

1.28 Critical factors in pillar extraction

Successful pillar extraction is a function of many parameters, and these parameters can be divided into two groups: controllable and uncontrollable. Unfortunately (in South Africa) because primary extraction was not done with a view to later pillar extraction, many of the controllable parameters in primary extraction become uncontrollable parameters in secondary extraction. These parameters include panel width, pillar width, bord width, mining height, pillar geometry and age of pillars.

In secondary pillar extraction, the controllable parameters are those that determine the mining layout and sequence. These parameters are:

- Overall mining direction
- Direction of splitting
- Sequence of fender extraction
- Snook size
- Extraction technique (full extraction or partial extraction), which determines the surface stability
- Number of seams mined.

The uncontrollable parameters are:

- Panel width
- Pillar width
- Bord width
- Mining height
- Depth below surface
- Geology, including overburden and interburden strata
- Caving mechanism
- Amount of scaling
- Presence, intensity of structures
- Existing roof conditions.

The effect of the above-mentioned parameters is summarised below.

1.28.1 Controllable parameters

Overall direction

It is well known that the direction of stooping should always start on the side closest to the previously mined panel and then mine away from it, and that mining between two goafed panels should be avoided as far as possible. If both sides of the panel are goafed, then extraction should be from the oldest panel towards the youngest.

The direction of extraction should always be consistent. The reason for this is that during the process of extracting a pillar, load is distributed to the surrounding unmined pillars. These cause micro-cracks to develop in the roof and the surrounding pillars.

The micro-cracks follow the same pattern as the stress contours. If the direction of stooping is changed, the directions of the stress contours will also change; implying that a new set of micro-cracks criss-crossing the ones that already exist will develop.

Direction of splitting

Pillars should always be split in the direction of the overall advance, i.e. into the main goaf and not parallel to it. The reason for this is that the main fractures in the pillar develop parallel to the goaf. If a pillar is split parallel to the goaf, the fender (one of the small pillars in each side of the pillar after it is split) closest to the goaf will be subjected to higher stresses and hence will be weakened by the fractures created.

Sequence of fender extraction

The fenders should always be extracted from the goaf to the solid.

Snook size

In pillar extraction, the aim is to remove all pillars completely. However, for various reasons this is always difficult to achieve. Snooks or even whole pillars will be left behind. Therefore, the snooks of the 'correct size' should be left to protect the pillars, control the stresses on the pillars to be extracted and prevent premature goafing of the immediate area.

Extraction technique

It is sometimes necessary and desirable to do partial high extraction mining, either by extracting pillars partially or by extracting some pillars completely and leaving some in situ. The aim of the partial high extraction is to minimise the disturbance to the overlying strata.

The design principles for partial high extraction methods are complicated. The stiffness of the pillars and the overburden strata should be determined. The partial high extraction layouts will be safe (meaning that the failure will be in a controlled manner) for as long as the stiffness of the system is greater than the stiffness of the pillars.

In very broad terms, partial high extraction at higher mining heights is predominantly controlled by restricting panel widths, thereby protecting the overburden beams from failure. At lower mining heights, the ratio of pillar width to height can more easily be brought into the range of non-violent failure. The panel width then becomes less important.

These considerations indicate that, in practice, it is more efficient at lower mining heights to opt for complete extraction of some pillars, leaving others in situ, and at higher mining heights it is more efficient to split all the pillars, but to restrict the panel width.

Number of seams mined

Many collieries in South Africa contain more than one seam that is economical to mine. If the seams are in close proximity, the mining of one seam may affect the subsequent mining of another seam due to factors such as parting failure, punching, subsidence and stress concentrations, which can result in difficult mining conditions.

Marketing constraints and coal quality have meant that from a strata control point of view the ideal sequence of mining in a descending order has been difficult to achieve.

In the Witbank area multi-seam bord-and-pillar mining is common. In Natal as many as four or five superincumbent seams have been exploited. Since the area produces high-grade anthracite and coking coal, high extraction methods are common. Coal reserves are usually limited and it is quite common to mine in areas that have been previously undermined or overmined.

Several combinations of methods for mining multiple seams have been tried. Table 0–1 shows the potential safety hazards associated with different multi-seam mining sequences and extraction methods (Hill, 1994).

Table 0–1 Potential safety hazards in multi-seam mining layouts (after Hill, 1994)

Method of mining		**Safety hazard**
Upper seam	**Lower seam**	
B&P	B&P	Spalling on pillars and parting collapse if P is thin and there is no superimposition
PE (2)	B&P (1)	Roof falls in L seam, parting collapse if P is thin
B&P (2)	HE (1)	Tensile zones and spalling in U seam when mining over goaf/solid boundary, floor collapse over incomplete goafs. High safety risk if P/h ratio is low
Remnant Pillar (1)	B&P (2)	Intersection collapse in L seam when mining under remnant
PE (1)	PE (1)	Simultaneous mining in both seams - roof falls in L seam
HE (1)	HE(2)	Preferred method of mining except where there are remnant pillars and water

L = lower
P = parting thickness
B&P = bord and pillar
U = upper
PE = pillar extraction
HE = high extraction

High extraction over bord-and-pillar workings

In any high extraction method, abutment stresses will be produced around the extraction panel. These abutment stresses are transferred above and below the plane of the workings into the surrounding strata. Where there is a bord-and-pillar layout in a lower seam, deterioration of these workings may occur. Subsequent pillar extraction of the lower seam pillars or use of the workings as travelling ways may be jeopardised as a consequence of overmining.

Overmining will change the stress distribution on the lower seam workings. As the abutment passes overhead, the pillars will experience an increase in load followed by considerable destressing. As goafing and settlement continue in the top seam, the lower seam pillars will be reloaded. The main factors affecting lower seam stability are:

- parting distance
- caving mechanism taking place in the extraction area
- stress distribution.

Increased parting distance will dissipate the effect of the abutment stress being transferred to the lower seam pillars. As the parting distance increases, the change in pillar load on the lower seam pillars will be less pronounced since the abutment load will be spread over more pillars.

Mining over goafs

Upper seam reserves have been written off in the past by operators who assume that they have been destroyed due to high extraction having taken place previously in the lower seam. However, several collieries in Kwazulu/Natal have successfully mined seams that have been undermined.

There are four characteristics of this type of mining:

i) Caving of the upper strata creates fracturing due to subsidence.
ii) Remnant pillars in the lower seam cause differential subsidence to occur. This creates areas of instability due to tensile zones over the pillar-goaf boundary.
iii) Remnant pillars cause stress concentrations, which will be transferred to the upper seam workings. This stress may be observed as pillar spalling or floor heave.
iv) Areas over incomplete goafs may be destressed.

Mining conditions in the upper seam will therefore depend on a number of factors.

- Type of strata

  The presence of a massive rigid layer in the overlying strata has the effect of dampening stress transfer and immediate subsidence from lower seam mining. Upper seam conditions can be expected to be poorer if the parting consists of shales compared with stronger sandstones. Disturbance of an upper seam has been showed to be less in the USA, where the lower mined out seam was overlain by a fairly thick shale bed which was, in turn, overlain by a strong sandstone bed (Stemple, 1956).

- Parting thickness

  The thicker the parting the less damage will occur. Stress from lower seam remnants can however be transferred over large vertical distances.

- Seam thickness

  It is recognized that the vertical extent of any disturbances will depend on the extraction height of the lower seam.

- Time interval

  It is generally recognized that the longer the time span between lower seam mining and upper seam mining, the better will be the conditions in the upper seam since equilibrium will have been achieved. Roof conditions will usually be better on a stable floor than on one which is subsiding.
- System of mining

  Where the mining of the lower seam has been complete, conditions are usually better than when incomplete mining has taken place since remnant pillars are minimal and subsidence profiles more even.

- Caving mechanism

  The expected conditions in the upper seam will be influenced by the caving mechanism of the lower seam and the subsequent subsidence. The caving mechanism can be completely or partially controlled by the bulking factor of the caved rock.

Where the ratio of parting thickness to lower seam height is high (>9) and bulking factor controlled caving has taken place, minimal problems need be anticipated. However, if this ratio is low (<6) and parting plane controlled caving has occurred, then there is a possibility of mining over incomplete goafs or voids. The possibility of a parting collapse will depend on the thickness of strata, the length of unsupported bridging strata, and the dimensions of and stress on the upper seam pillars.

Mining under goafs

Mining in a descending order such that each seam worked is under the top seam goaf is normally the preferred method of multi-seam mining. It usually works well where good caving and consolidation have taken place. Problems can occur if the parting is thin and the upper seam workings are flooded. Time must be allowed for the goaf to settle before the bottom seam is mined. Mining under goafs with thin partings is common in the Kwazulu/Natal collieries.

Remnant pillars left in upper seams can cause severe damage when mining in a seam below due to the high stresses, which are transferred. Developments under remnant pillars can result in major intersection collapses. The mechanism is similar to the case of pillar extraction over bord-and-pillar workings where large tensile zones can be created.

Methods of reducing the risk of roof collapse include reducing the road width, staggering the junctions and changing the roof support.

Simultaneous mining

Simultaneous mining is the mining of two (or more) seams in the same area at the same area extraction rate. The horizontal distance between the two face lines in each seam is kept constant.

This type of mining has been carried out in Natal in the past, especially where it has been difficult to keep lower seam roadways open for complete development under a goaf. It is normal for the coal to be transported out through one seam only.

Two methods have been employed. These methods are:

(i) Simultaneous stooping in both seams (I)

Superimposed pillars are developed in both seams. Stooping takes place simultaneously in both seams, with the top seam extraction line being about half a pillar ahead of the bottom seam extraction line. Problems can be experienced if goafing is not consistent. Some collieries spent many years experimenting with different top seam leads over the lower seam extraction line to find the optimum distance.

(ii) Simultaneous stooping in both seams (II)

The bottom seam is first developed in a bord-and-pillar layout. The pillars are extracted according to a splitting system. As splits are developed, drilling and firing drop the parting. The top seam is recovered by top coaling from the top of the parting.

Simultaneous mining has had mixed success, probably due to the reliance on good caving of the parting between the two seams.

From all the above it can be concluded that the preferred method for high pillar extraction in a multi-seam environment is from the top to the bottom seam.

1.28.2 Uncontrollable parameters

Panel width, pillar width, bord width and mining height

An investigation was undertaken by Roberts et. al. to determine accurately the loads on pillars in a typical bord-and-pillar coal mining panel. Loads are normally calculated using tributary area theory, which simply determines the proportion of the overburden load that is carried by each pillar within a particular regular geometry. The span of the panel, the properties of the overburden and the presence of barrier pillars are not considered. An attempt was made to incorporate all these factors into a single formula, and to determine the impact of erroneous load calculations on the Salamon and Munro formula (1967). Ultimately this proved to be unnecessary, as it was shown that the overburden did not behave elastically in most of the failed cases used to derive the formula. Tributary area formula was therefore a reasonable estimation of load for the failed cases. It is also the most conservative estimate of pillar load, making it appropriate for design purposes.

Modelling investigated the influence of panel width and overburden stiffness. The effect of introducing laminations into the overburden model was also investigated, as this effectively allows for fine-tuning of the overburden stiffness. The code used for the modelling investigation was LAMODEL, which treats the overburden as a stack of frictionless laminations. It is a boundary element program where the seam is treated as a displacement discontinuity (effectively, a crack). The effective overburden stiffness is a product of the lamination thickness and the elastic modulus of the overburden material. Varying the stiffness by a factor of 100 altered the central pillar APS by less than 1 per cent. It was noted that pillar load decreased with increasing overburden stiffness.

Equivalent rib-pillar models were generated using LAMODEL, Elfen (discrete elements in plane strain) and Phase2 (continuum plane strain with smeared discontinuities). The plane strain results were comparable, and indicated stresses up to 8 per cent less than those obtained from LAMODEL. When a 30^0 contact friction angle was introduced on the contacts the APS decreased by 16 per cent from the frictionless case. Three-dimensional modelling was also undertaken using Elfen and it was found that the APS was 8 per cent less than that obtained from LAMODEL. Stress distributions were examined in some detail, demonstrating how high contact friction increases the confinement within the pillar.

The primary finding of this work is that pillar loads are probably under-estimated in most cases, but not in cases where the overburden has failed. It must be emphasised that the stress on a pillar in a horizontal seam cannot exceed that predicted by tributary area theory.

As discussed in the literature review that Salamon and Munro (1967) detailed the statistical analysis of 27 cases of collapsed pillars and 98 intact pillars. A probabilistic notion of safety factor was used where:

$$Safety\ Factor = \frac{Strength}{Load}$$

Load is calculated using the modified cover load or Tributary Area Theory in which 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. The majority of bord and pillar panels in South African collieries fulfil these conditions.

Strength is taken to mean the strength of a coal pillar as opposed to the strength of a coal specimen. The formula for strength was given as:

$$Strength = Kh^{\alpha} w^{\beta}$$

where k is 7 176 kPa
α is -0.66
β is 0.46.

As can be seen from the above equations, the strength of pillars is a function of pillar width and mining height. Increasing the pillar width increases the pillar strength, and increasing the mining height decreases the pillar strength.

Bord width has no effect on the pillar strength, but it does have an effect on the pillar load. As the bord width increases, the load on the pillars increases, thus decreasing the safety factor.

The bord width will also determine the stability of the interburden, which is one of the critical parameters in pillar extraction. The basic beam equations for gravity-loaded beams with clamped ends are:

Maximum bending stress $\sigma_{xy(max)} = \frac{qgL^2}{2t}$ (MPa)

Maximum shear stress $\tau_{xy(max)} = \frac{3qgL}{4}$ (MPa)

Maximum deflection $S_{max} = \frac{qgL^4}{32Et^2}$ (mm)

where *L* is the roof span (width of roadway)
t is the thickness of the roof layer
q is the density of suspended strata
g is the gravitational acceleration.

These equations highlight the importance of variation in bord width. Any change in bord width will significantly affect the response of the strata to load. For example, a 33 per cent increase in bord width from 6 to 8 m results in a:

216 per cent increase in roof deflection
78 per cent increase in roof tensile stress (since the tensile strength of a rock 10 to 20 times weaker than the compressive strength this is the most important increase)
33 per cent increase in shear stress over the roadway abutments.

Geology

It is seen from the above equations as well as in practice that the maximum bending stress, shear stress and deflection are functions of strata thickness. The thicker the strata, the more stable the workings.

The behaviour of the overburden strata is possibly the most critical factor as it also affects the mining method, the type of mining equipment that can be used, the support required during development and stooping, the caving mechanism, the surface damage and the stress environment.

The composition of the overburden strata is one of the critical factors affecting the formation of a goaf during stooping and loading. Unlike the case in bord-and-pillar sections, the load on the pillars in stooping sections changes constantly due to the dynamic nature of the mining process. When competent massive sandstone, which does not break during initial goafing, or a dolerite sill overlies the coal seam, the load on the pillars will be higher than after failure of the sill or sandstone. This is due to the additional load that has to be borne by the pillars in the vicinity of the goaf edge to support the overburden spanning the goaf area.

Competent strata layers, such as thick dolerite sills and massive sandstone layers, can result in the temporary arrest of caving at the base of these competent layers. Dolerite sills in particular bridge over the goaf and deflect elastically. However, when the free span at the base of the sill exceeds the critical span dimensions, it leads to the structural but non-violent failure of the sill. This has been observed above various longwall panels in South Africa.

When any form of total extraction is being contemplated, the effect on the surface must be taken into account.

If a dolerite sill overlies the coal seams, two options are available:

- Designing the panels to be narrow enough to ensure that the dolerite sill does not fail. This will cause the sill to bend without failing and will cause less surface subsidence than when the sill fails.
- Designing the panels to be wide enough to ensure that the dolerite sill does fail. This is desirable to avoid any excessive load on the pillars being extracted.

When the roof stratum is relatively weak and incompetent, the high compressive stresses in the vicinity of the abutments are sufficient to cause shear failure of the strata. The stress-induced fractures that develop in this stratum as a result of these stresses are near vertical. As the lower roof stratum in a mined-out area is in tension, gravity will cause a highly fractured roof stratum to cave readily. Because there are no competent roof layers, caving of the roof is continuous and extends to surface.

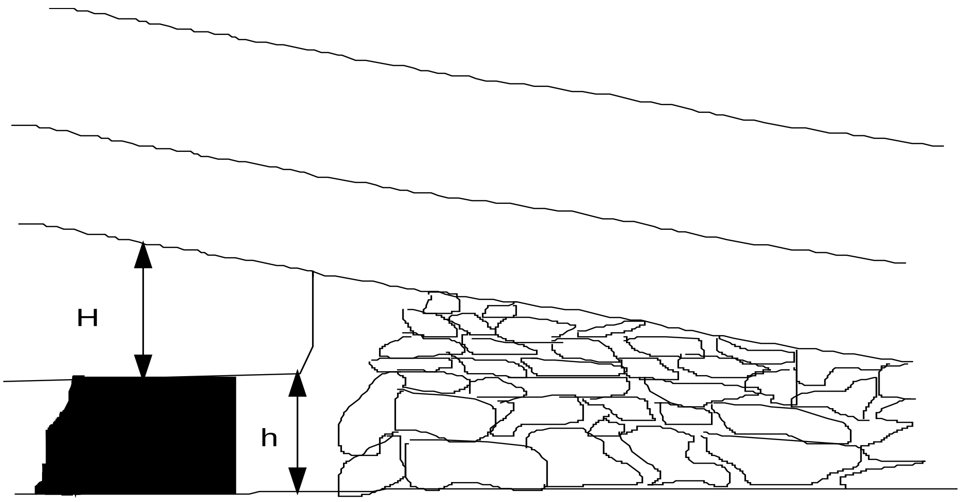
Caving mechanism

The caving mechanism is also an important parameter in both single-seam and multi-seam pillar extraction.

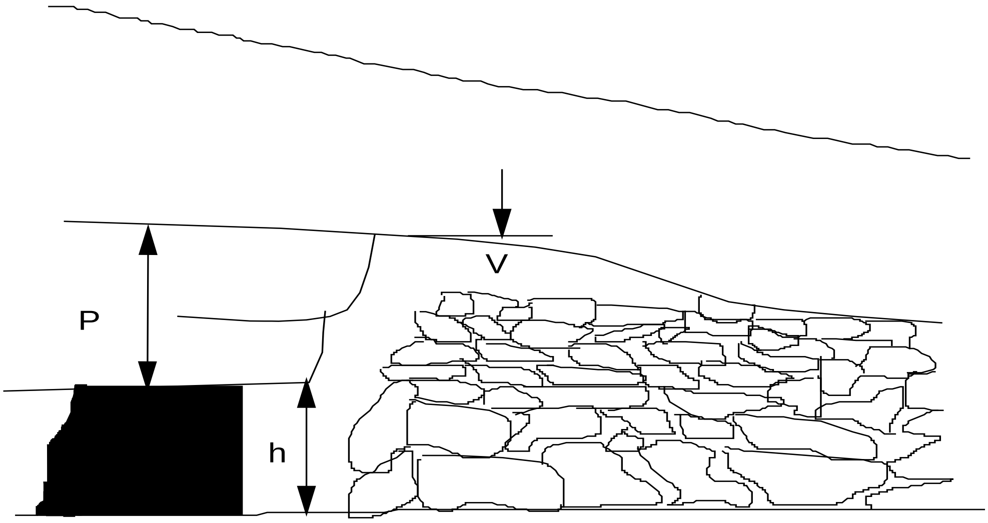
Two types of caving mechanism have been identified (Hill 1994). For small spans the height of caving will be determined by the caving angle of the overlying strata. These mechanisms are:

1. Bulking-factor-controlled caving (Figure 0–1 (a)) in which the height of caving will be determined mainly by the bulking factor of the caved material. In this mechanism, caving continues until the goaf material is in contact with the upper strata. As the pillar-extraction line moves away, compaction of the goaf will take place. Bulking-factor-controlled caving is typical of conditions where the strata consist of shales and mudstones and are therefore relatively weak.

2. Parting-plane-controlled caving (Figure 0–1 (b))in which the caving height is determined by the location of dominant parting planes within the roof strata. A waste void will initially form between the caved waste and the overlaying strata. From the extraction line into the goaf area, the strata will converge until they make contact with the caved rock. Parting-plane-controlled caving is typical in conditions of alternating layers of different strengths, where the layers are identified by well-defined parting planes. Where thick sandstone layers are present, incompetent caving and therefore voids can be expected, and as the pillar-extraction line advances, consolidation will take place in the goaf.



a) bulking factor controlled caving



a) parting plane controlled caving

Figure 0–1 Two caving mechanisms as identified by Hill, 1994

Amount of scaling

As mentioned earlier, pillar strength is a function of pillar width. The strength of pillars increases as the pillar width increases. However, the pillars deteriorate with time, and the extent of this deterioration should be known in order to accurately calculate the strength of pillars.

As the pillar width decreases, the bord width increases. The effect of bord width was discussed above. As it increases, the stability of the workings decreases.

Effect of scaling and determination of amount of scaling is discussed in another COALTECH project (Task 6.9.1). Therefore, the details of this work are not presented in this report.

Geological discontinuities

Like most rock types, coal contains natural discontinuities, which have an effect on its strength. In general, the greater the intensity of the discontinuities, the weaker the rock mass becomes. The strength of coal pillars should therefore also be affected by the density of the discontinuities in the coal.

These discontinuities are therefore important in designing layouts and support patterns. The stability of the roof also decreases as the density of the discontinuities increases.

The direction of the discontinuities is as important as the density. Although in some cases even major discontinuities may not be critical, in others minor slips become very important due to their direction. Therefore, in order to accurately determine what mining layouts and support patterns are likely to be unstable, all the geological discontinuities and their directions should be known in advance.

1.29 Conclusions

Pillar extraction takes many forms and mines have adopted methods of removing individual pillars to suit their particular needs. In 'traditional' stooping, it was recommended practice to remove or destroy all snooks in order to allow the goaf to cave thereby relieving the stress on the caving pillar line. Many of the pillar extraction methods now used deliberately leave pre-designed snooks that prevent immediate caving but will crush over time. Advantages of these methods are:

- the absence of a caving line, thus removing an area of high risk,
- immediate water table disturbances, and
- elimination of the problems/dangers associated with goaf 'hang-ups' and sudden goaf collapses.
- Improved ventilation flows and methane drainage.

One major disadvantage of keeping up the goaf by the use of pre-designed snooks or by the use of checker-board mining is the uncertainty of when the snooks or remaining pillars are going to crush and allow the overburden strata to settle.

Contrary to previously held views, mines now do not believe that pillar extraction is a less safe method than pillar development. This may be because pillar extraction is now done by continuous miner, often by means of remote control, and also that the incorporation of section employees in more risk assessment procedures has introduced a greater awareness amongst the underground operators of the inherent dangers in pillar extraction. Also, more use is now made of ‘partial’ pillar recovery and checker-board systems where the formation of a goaf edge is prevented, thereby removing a hazardous area from the system.

The cost of pillar extraction in comparison to pillar development is reported to be higher by some mines but lower by others. Much depends on a mine’s costing procedures and whether pillar extraction follows directly after pillar development or whether old panels have to be rehabilitated.

Pillar extraction by means of shortwall equipment has been done successfully but a particular problem can be the rate of retreat through the pillars. Over a face length of say 90 m made up of 4 fifteen metre square pillars and 5 six metre wide bords, coal is present over only two thirds of the shortwall face length and the other third is ‘air’. Careful consideration must be given to the logistics of utilising what is considered to be a highly capital intensive method for the recovery of pillars.

The recovery of old pillars by underground pillar extraction has been shown to be feasible in the number 4 Seam and the number 2 Seam in the Witbank Coalfield. Experience is being gained which should be beneficial to the industry in the wider application of pillar extraction to other parts of the Coalfield where suitable reserves may be found.

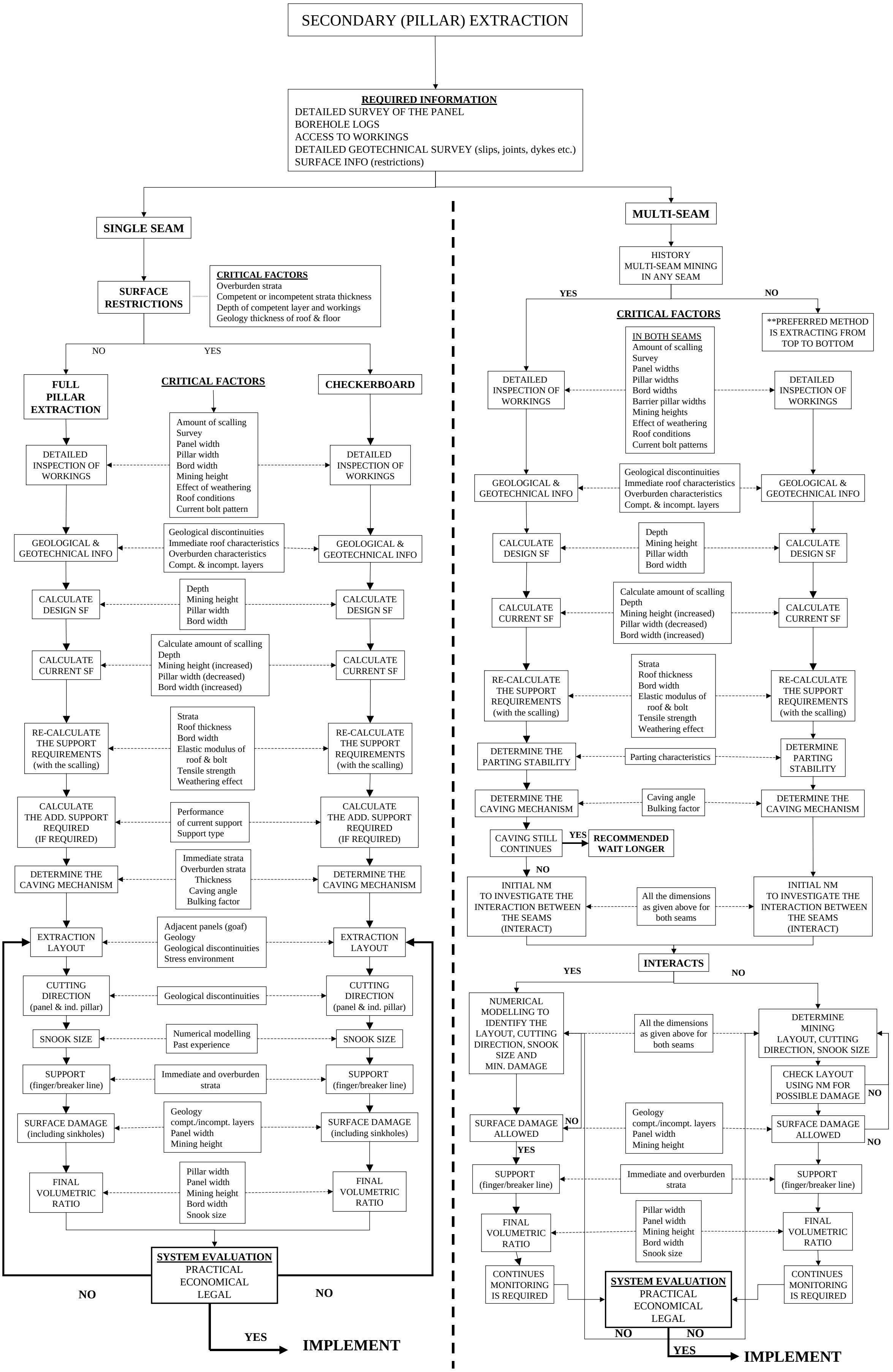


Figure 0–2 The critical factors in the design of pillar extraction

Effect of panel geometry in pillar extraction

1.30 Introduction

As mentioned earlier that the magnitude of the load acting on the pillars in the active mining zone is a function of the panel geometry in pillar extraction. The magnitude of surface damage is also a function of panel width. In order to investigate the effect of panel width in pillar extraction, this study was conducted.

The effect of panel geometry on face-pillar stability and artificial barrier pillar stability was investigated. The effect of backfilling on in-pillar and barrier pillar loading was also investigated. LAMODEL, a boundary element program specially suited to coal modelling, was used to analyse different layouts.

1.31 LAMODEL

LAMODEL is a boundary element code, which models tabular excavations as displacement discontinuities (DD's). These DD's physically represent cracks, which is appropriate in the gold and coal mining environment where seam height is typically less than one per cent of the maximum dimension of the mining extent. The region of interest is discretised by regular gridding with a fixed square element size. The geometry of the modelled region is rectangular. Solid and void areas are specified on the DD plane to model pillars and excavations. A number of mining steps may be simulated by changing elements from solid to void and vice versa when backfill is modelled.

Seam stresses (in the solid) and convergence (in the excavated areas) are the primary outputs of the program. In shallow excavations, the proximity of the surface may influence the stresses and displacements within the seam. LAMODEL models this effect by placing a fictitious seam in space such that a traction-free surface, representing ground level, is created.

LAMODEL is different from continuum boundary element codes in that the overburden is treated as a stack of regularly spaced frictionless laminations. The formulation for this approach is based on the theory of thin plates and it is assumed that the beds are always parallel and that no shear stress or cohesion is present along the contacts. The size of the laminations is user-specified. The effect of this assumption is to reduce the stiffness of the overburden such that convergence is typically higher than for homogenous models. It is also possible to specify symmetry conditions on any edge of the model in LAMODEL, so that infinitely repeating geometries can be modelled.

1.32 Model description

Five different layouts were used in the analysis. These layouts are presented in Figure 0–1 to Figure 0–5.

These layouts are based on the changing pillar extraction options on pillar extraction stability to include:

- three pillars mined leaving one row barrier (Model 1) (Figure 0–1),
- two pillars mined leaving one row barrier (Model 2) (Figure 0–2),
- three pillars mined leaving a two row barrier (Model 3) (Figure 0–3),
- two pillars mined leaving a two row barrier (Model 4) (Figure 0–4),
- common pillar extraction layout (all rows mined) (Model 5) (Figure 0–5),
- backfill models of first four models (Model 1, 2, 3 and 4) (Figure 0–1, Figure 0–2, Figure 0–3 and Figure 0–4)

The common pillar extraction practice of mining the total pillars in rows and columns, without leaving any artificial barrier pillars in the centre of panel, was also modelled, Model 5. The results from Model 1 to 4 were then compared with Model 5.

For each option, the change in mined shape from rectangular (one direction) to square to rectangular (in the other direction) were modelled so as to determine progressive changes in pillar, abutment and barrier stress distribution.

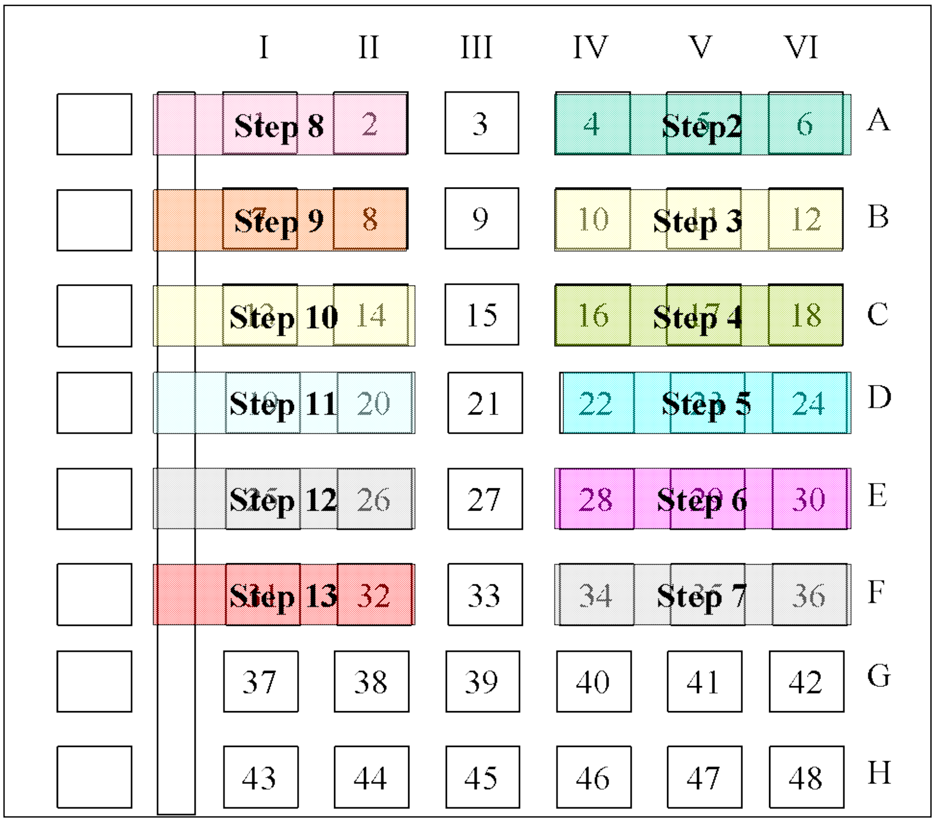


Figure 0–1 Model 1, 3-Rows mined, 1-Row left as barrier

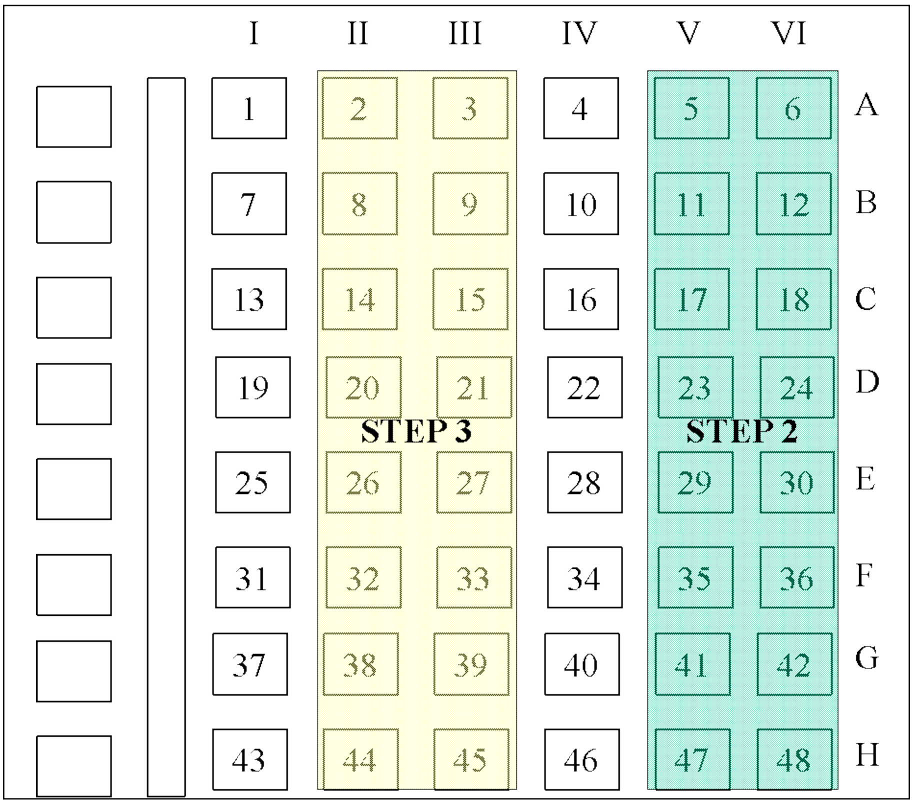


Figure 0–2 Model 2, 2-Rows mined, 1-Row left as barrier

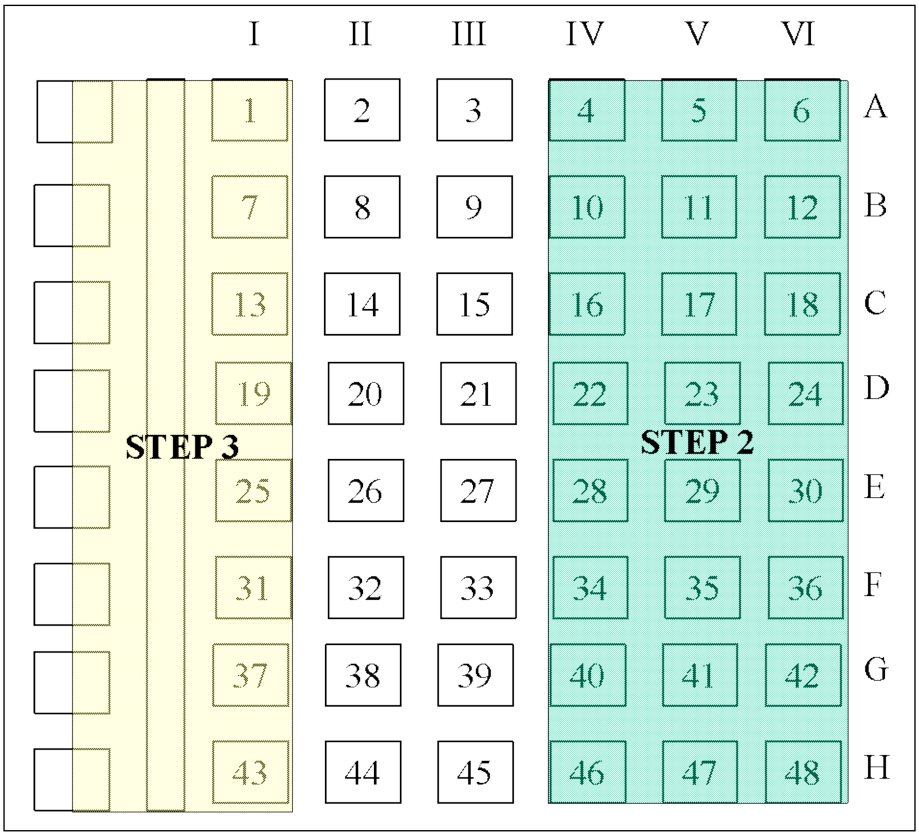


Figure 0–3 Model 3, 3-Rows mined, 2-Row left as barrier

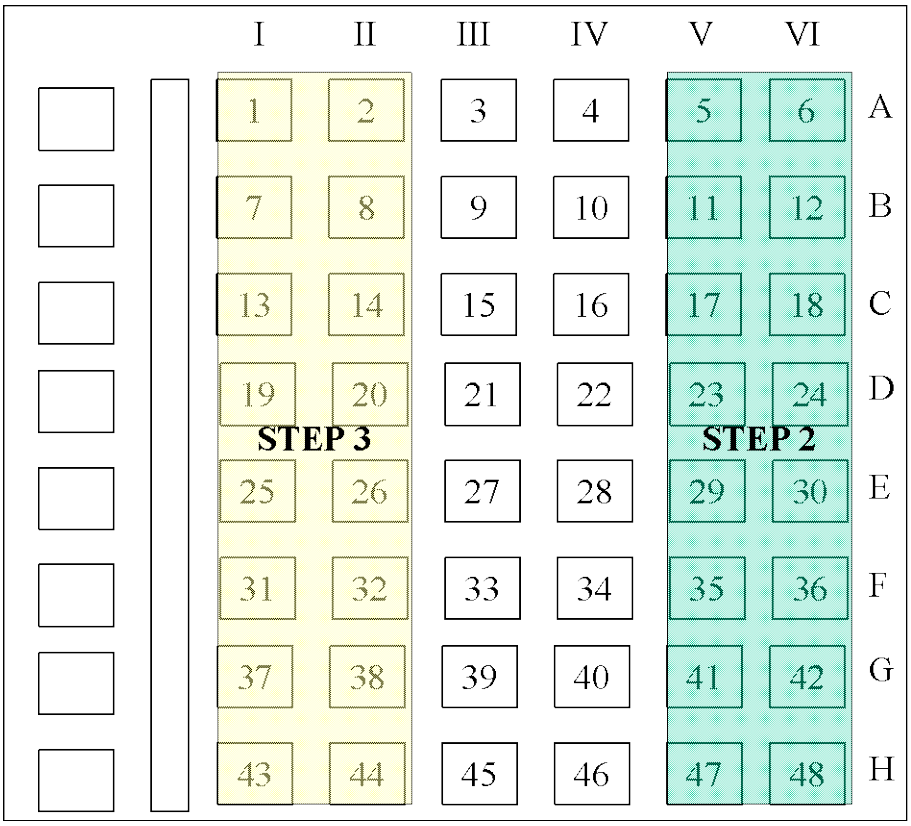


Figure 0–4 Model 4, 2-Rows mined, 2-Row left as barrier

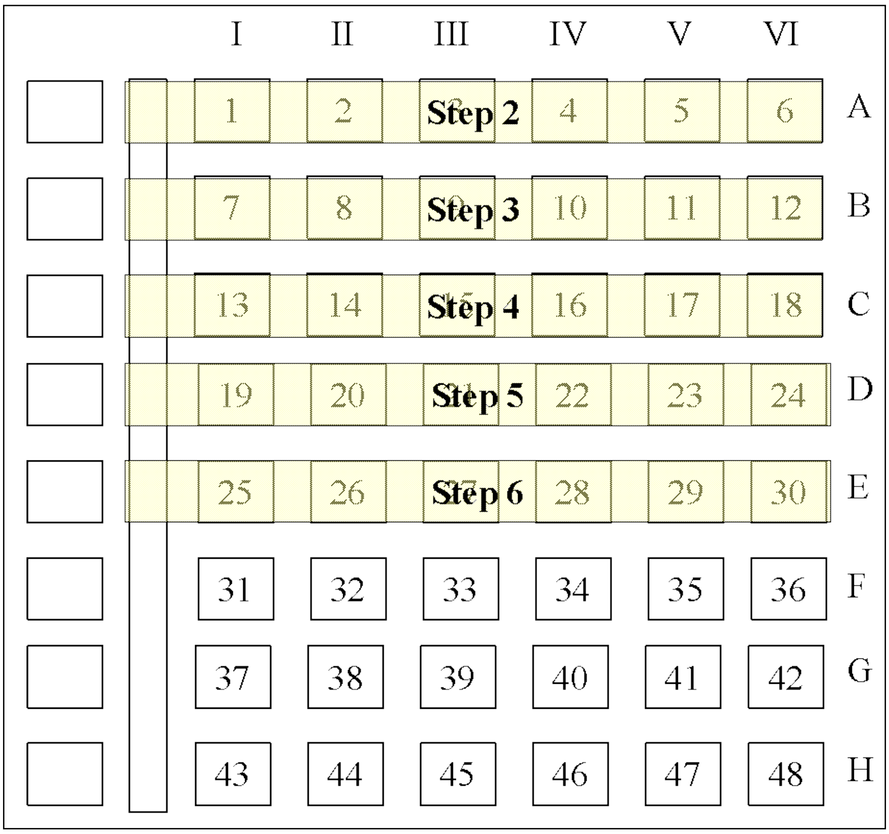


Figure 0–5 Model 5, All rows taken, common pillar extraction method

1.33 Material properties

The following material properties were used throughout the study:

Overburden Elastic Modulus (E_{host}) = 30 GPa

Coal Elastic Modulus (E_{coal}) = 4.0 GPa

Overburden density (γ_{host}) = 0.027 MN/m^3

Coal density (γ_{coal}) = 0.016 MN/m^3

Overburden Poisson's Ratio (ν_{host}) = 0.2

Coal Poisson's Ratio (ν_{coal}) = 0.3

Pillar width (w_{pillar}) = 17.5 m

Mining height (h) = 4.5 m

Bord width (b) = 7.5 m

Depth below surface = 132 m

Backfill height ($h_{backfill}$) = 2.5 m

Backfill material properties are discussed in detail further in this report.

As it can be seen from the above material properties that the overburden material was assumed to be significantly stiff.

1.34 Results

1.34.1 Effect of leaving centre pillars as barriers

As seen in this study that leaving one or two rows of pillars in the centre of the panel as artificial barrier pillars has two major advantages. First of all, it will limit the panel width, which will decrease the stress on the face pillar being extracted. Secondly, because it will limit the panel width the amount of surface subsidence will be less compared to the full panel width extraction. Although this second phenomenon cannot be modelled using numerical modelling tools, an analytical model is being investigated as part of Task 2.4

In order to simulate the effect of artificial barrier pillars on stress in the face pillars, Model 1 was constructed. The results are shown in Figure 0–6. The pillar stress is calculated on pillars, which were one row behind the completed line of pillars being mined. For example, in Figure 0–6, in mining step 1, the stress on pillar 39 was determined after mining the bords (primary production), and in mining step 2, the stress on pillar 11 was determined (first row of 3-rows mined), in mining step 3 the stress on pillar 17 was determined (second row of 3-rows mined), and all the results were extracted using this process.

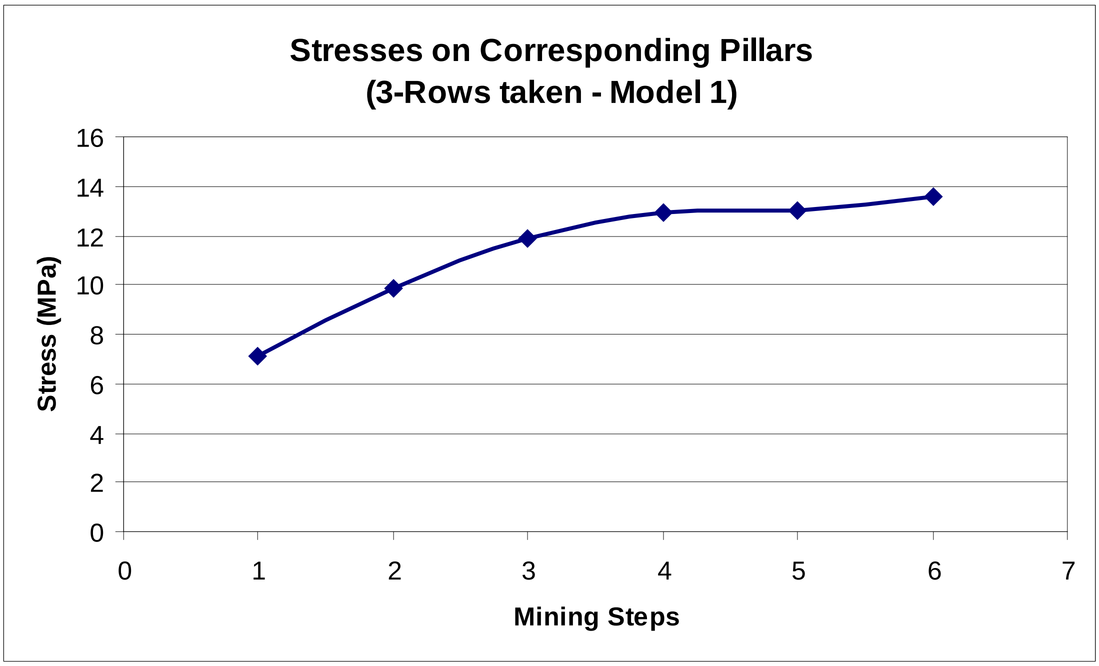


Figure 0–6 Effect of leaving artificial barrier pillars in the centre of the panel

Figure 0–6 indicates that after mining step 3 the increase in stress acting on the face-pillars is nearly constant. This highlights the importance of the change in mined shape from rectangular (one direction) to square to rectangular (other direction).

This comparison was also done between Model 1 and 5 in order to determine the significance of this phenomenon. The results are presented in Figure 0–7. This figure indicates that in Model 5, which represent the common pillar extraction practice, the stress on the face-pillars does not flatten out as it is the case in Model 1. Also, there are significantly higher stresses on the face-pillars in Model 5 than Model 1. This is shown in Figure 0–8. This figure indicates that in mining step 6 (the second last row of the right hand side of the panel) the stress on the face-pillars in Model 5 is 45 per cent higher than Model 1 face-pillars.

From these results it is concluded that there is a great advantage of leaving artificial barrier pillars in the centre of the panel with respect to stresses on the face-pillars.

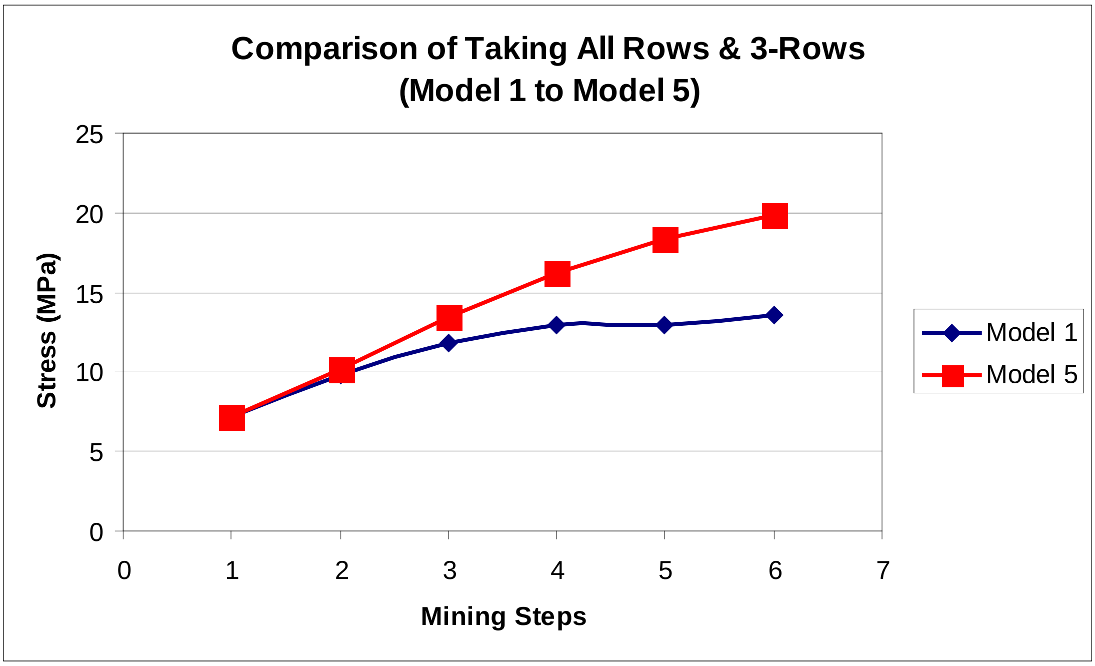


Figure 0–7 Comparison between the Model 1 and 5 with respect to stress on face-pillars

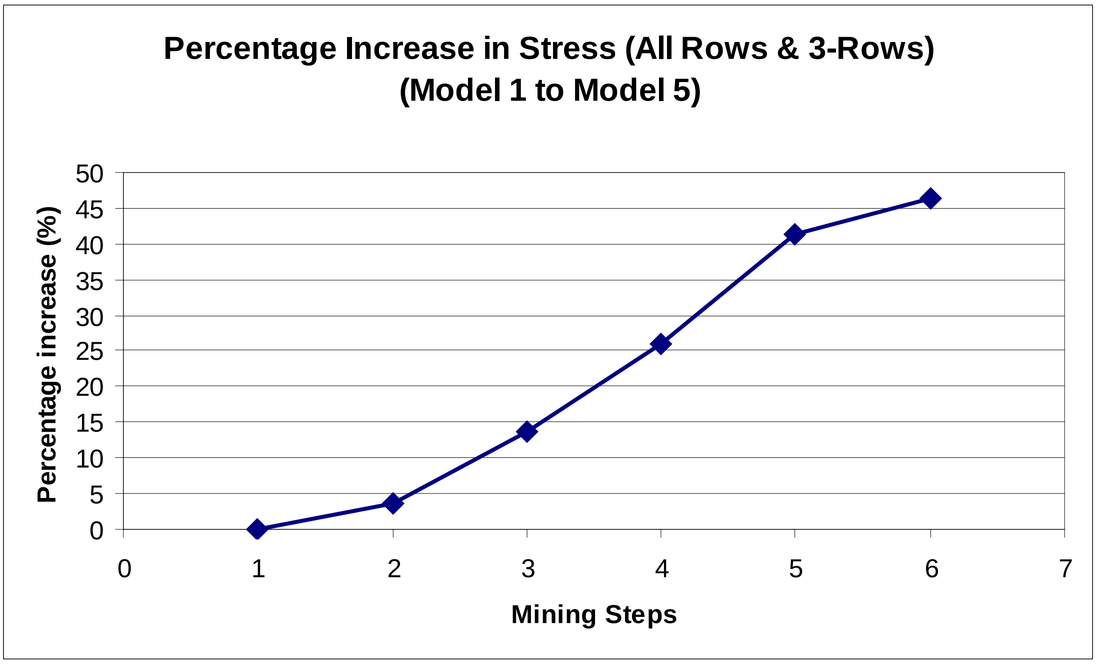


Figure 0–8 The percentage difference between Model 1 and 5

1.34.2 The safety factor of the face-pillars

In the development of the safety factor concept (Salamon, 1967), the load acting on the pillars was calculated using the Tributary Area Theory. The reason for that was in the development of the strength formula, the maximum likelihood method was used with the failure load of the pillars that failed calculated using the Tributary Area Theory. Therefore, the load acting on the pillars extracted from the numerical modelling would not give the appropriate answer in determining the safety factor of pillars. However, in order to demonstrate the constant safety factor of face pillars after the square to rectangular transaction zone, Figure 0–9 was plotted. The blue line in this figure represents the stress on the face-pillars (right-hand y-axis), and the red line represents the safety factor of the face pillars (left-hand y-axis) calculated using the Salamon and Munro's strength formula with the load extracted from the numerical modelling.

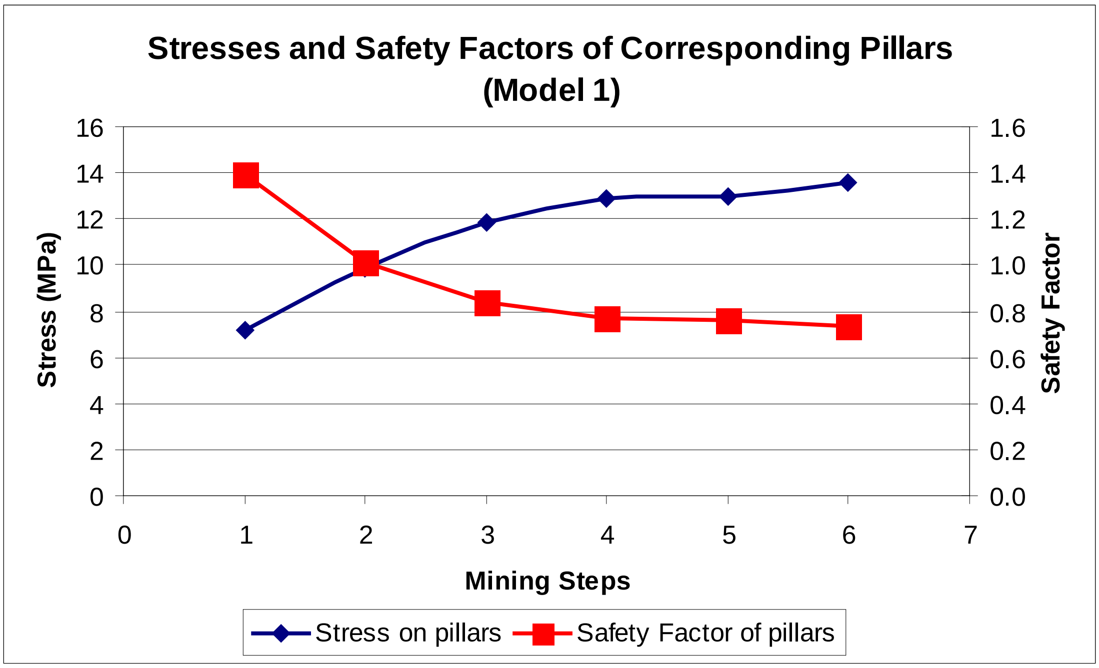


Figure 0–9 The safety factor of face-pillars

The above figure indicates that the safety factor of the face-pillars also becomes nearly constant as the stresses becomes constant.

1.34.3 Abutment stresses

During the initial stage of the numerical modelling it became apparent that the stresses on the artificial barrier pillars increases as the number of mined pillar rows increases, and as the number of artificial barrier pillar rows decreases. This phenomenon is shown in Figure 0–10. The stresses associated with each mining step given in this figure, obtained from the centre pillars. Only three mining steps were considered in the analysis. The stresses in mining step 1 were extracted from the centre pillars after mining the bords. Stresses in mining steps 2 and 3 were extracted from the centre pillars after mining the right-hand and left-hand sides of the panel respectively.

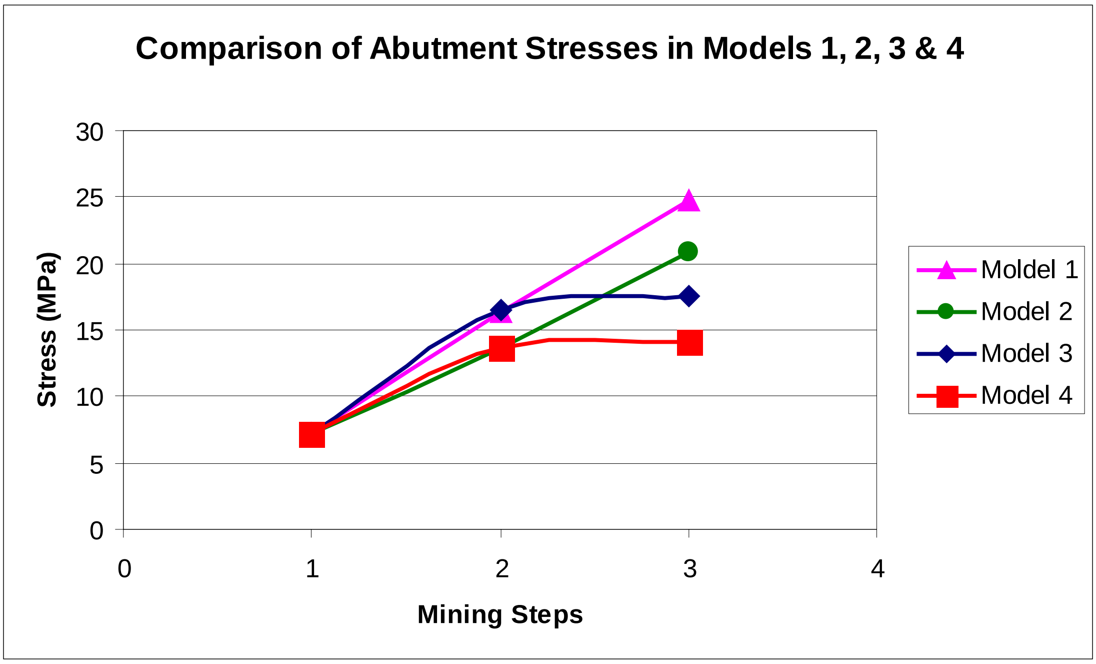


Figure 0–10 The stresses acting on the artificial barrier pillars as the mining takes place

This figure indicates that as expected, Model 1 gave the maximum stress and Model 4 gave the minimum artificial barrier pillar stress. The reason is that in Model 1, only one row of artificial barrier pillar was left and three rows were mined on each side of the barrier pillars. In Model 4 only 2 rows of pillars were mined and two rows of barrier pillars were left.

Based on this figure it can be concluded that mining three rows of pillars on either side of the artificial barrier pillars and leaving two rows of artificial barrier pillars is the most effective layout for the panel (Model 3). This can be directly related to stability of the artificial barrier pillars and the extraction ratios. While stress on the artificial barrier pillars is 50 per cent less in Model 3 than in Model 1, the overall extraction gained by leaving one rows of pillars rather then two rows is less than 20 per cent.

1.34.4 Effect of backfilling

As part of the study, the effect of the backfilling on stability of the artificial barrier pillars was also investigated.

It is well known that the modelling of backfilling and backfill material has always been difficult for various reasons.

Backfill was modelled using a non-linear gob (goaf) model within LAMODEL. Goafed areas were modelled using a strain-hardening formula, which is well suited to modelling of backfill. An exponential stress/strain curve, with a linear increase in tangent modulus (with increasing strain), describes the behaviour of the material. The associated formula is presented below:

$$\sigma = \left[\frac{E_i \sigma_u}{E_f - E_i}\right]\left[e^{a\varepsilon} - 1\right]$$

$$a = \frac{E_f - E_i}{n\sigma_u} \qquad \textbf{\textit{(1)}}$$

Where E_i is the initial tangent modulus

E_f is the final tangent modulus (at σ = σ_u)

σ_u is the virgin stress

a is a parameter representing the degree of non-linearity of the curve

n is the "gob factor" – a linear reduction in *a* which accounts for a partial fill

The curve is then graphically represented as follows:

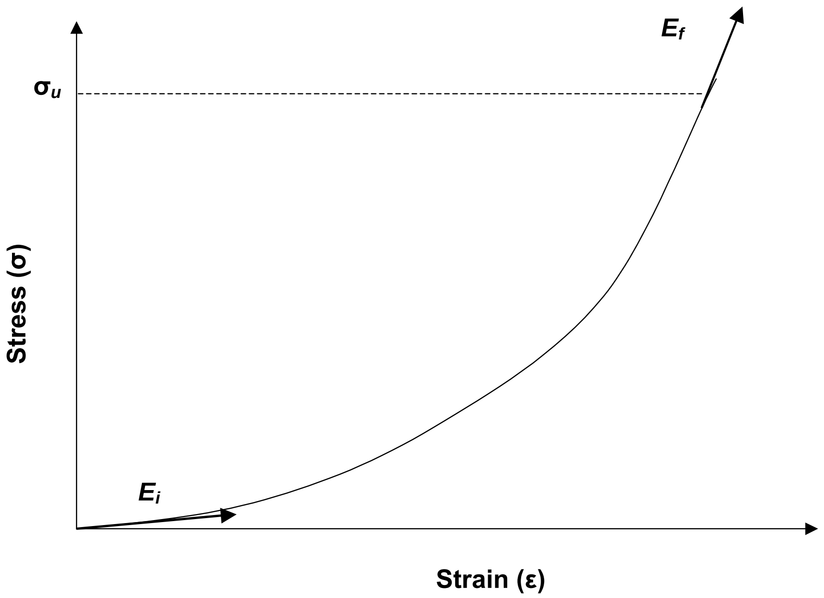


Figure 0–11 Backfill material curve used in the models

The following values were used for the analysis:

E_i	20 MPa
E_f	3500 MPa

σ_u 3.564 MPa
n 1

In addition, the Poisson's ratio is assigned a value of 0.1. These backfill properties are based on a study conducted by J. Ryder on Sigma Colliery backfill project. However, the backfill curve given in Figure 0–11 was upgraded so that the coal stiffness was approximated at 20 per cent strain. This allows modelling of stiffer backfill. Also, this is believed to represent both weak-ashfill at low strain and stiffer-cemented ashfill at high strains. Although these parameters represent a generic backfill material, it is strongly recommended that backfill material properties should be determined prior to underground application.

The results obtained from the backfilled and non-backfilled models are presented in the following table. This table simply shows the percentage stress reduction due to backfilling on the artificial barrier pillars. Note that "Left" and "Right" indicate the stress reductions after the left-hand and right-hand side of the artificial barrier pillars mined (right-hand side of the barrier pillars mined first).

Table 0–1 Percentage stress reductions on the artificial barrier pillars due to backfilling

	Left	**Right**
Model 1	16.7	10.8
Model 2	13.9	6.9
Model 3	17.6	15.1
Model 4	8.6	7.6

This table indicates that total stress reduction varies from 8,6 to 17,6 per cent, depending on the model, Model 3 shows the maximum reduction. From this result it should be highlighted that in the artificial barrier pillar models, Model 3 (mining 3-rows, leaving 2-rows) gave the best combination with respect to the abutment stress. Therefore, it can be concluded that, irrespective of backfilling, Model 3 is the best combination for the section.

1.35 Conclusions

The following conclusions were extracted from the above results:

- Mining 3-rows of pillars in either side of the artificial barrier pillars and leaving 2-rows of artificial barrier pillars is the most the effective layout for the given dimensions and panel layout (Model 3). The belt can also be constructed between these two barrier pillars.

- Model 3 will also be more beneficial in terms of abutment stresses, should it have decided to use backfilling.

This study is based on certain assumptions and certain parameters. Therefore, it is strongly recommended that a detailed numerical modeling program, including nonlinear modeling, should be conducted in order to obtain more accurate results with respect to stability of the artificial barrier pillars and the overlying sandstone layer. This may result in different combinations and layouts than being recommended.

Surcharge load in pillar extraction

1.36 Introduction

This section of the report details the calculation of the surcharge load in pillar extraction, which is due to the overhang and abutment angle.

1.37 Calculation of surcharge load in pillar extraction

As mentioned earlier in the report that recommended safety factor of pillars is 1.8 for pillar extraction. The reason for this is that the extra surcharge load caused by the overhang.

It is well known that the surcharge load has been distributed amongst the pillars at the face. Mark (1997) suggested that the active mining zone (AMZ) is $5\sqrt{H}$, where H is depth below surface.

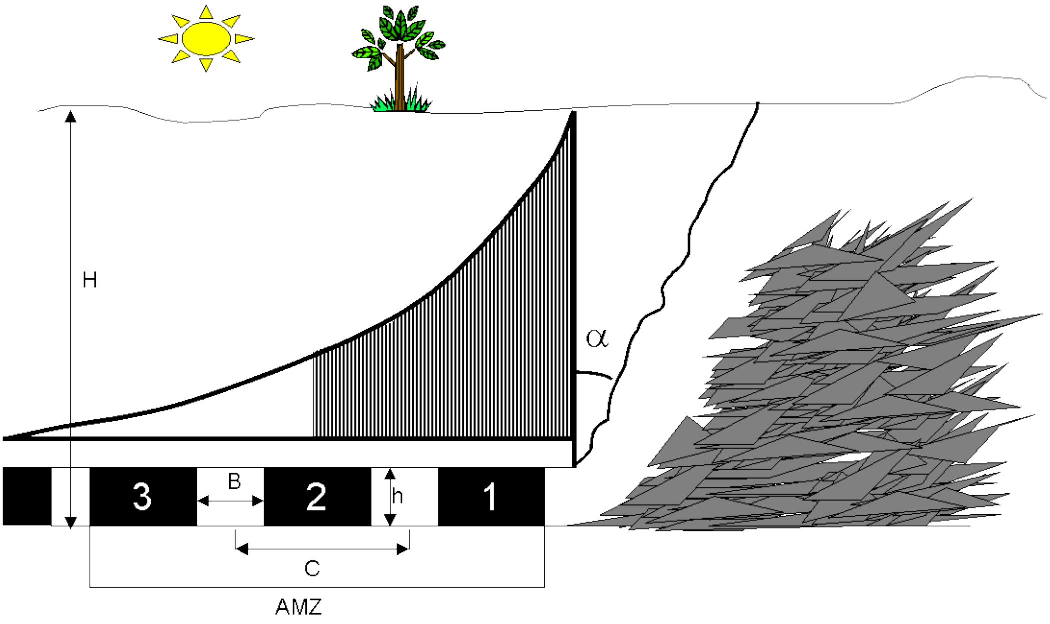


Figure 0–1 Surcharge load due to overhang in pillar extraction

However, experiment conducted at Bosjesspruit Colliery as part of Task 2.13.1/2 showed that the AMZ is $3.2\sqrt{H}$.

Bosjesspruit Colliery experiment and the numerical modeling results also indicated that the surcharge load distribution of pillars is as follows:

Pillar number 1: carry 92.5 per cent of the surcharge load
Pillar number 2: carry 6.25 per cent of the surcharge load
Pillar number 1: carry 1.25 per cent of the surcharge load

The surcharge load acting on the pillar can be calculated as follows:

Weight of the wedge is:

$$Weight = \left(\frac{H * \tan \alpha}{2} \right) HCgq$$

where H is depth below surface (m)
α is abutment angle (^{o})
C is centre distance (m)
g is density of overburden
q is gravitel acceleration
g is gravitational acceleration

The load applied by the wedge is:

$$L_S = \frac{weight}{w^2}$$

where w is pillar width (for rectangular pillars $w_1 x w_2$)

The total load acting on the pillar is then:

$$L_T = TAT + L_S$$

where TAT is Tributary Area Theory load and is:

$$TAT = 0.025H \frac{C^2}{w^2}$$

Then, the safety factor of a pillar in the AMZ is

$$SF = strength / L_T$$

where strength is calculated using Salamon and Munro's strength formula.

These equations highlight the importance of the abutment angle. Figure 0–1 shows the effect of abutment angle on safety factor of pillars within the AMZ. As can be seen that the safety factor of a pillar can decrease from 1.73 (for 0^o very soft strata) to 1.14 (for 30^o strong sandstone strata). This implies an 80 per cent reduction in safety factor, indicating that the pillars within the AMZ will have relatively higher safety factors in soft strata then the relatively competent strata. However, disadvantageous of this is that in a relatively soft strata the roof will fail in unpredictable manner in which the control of goafing may be more difficult.

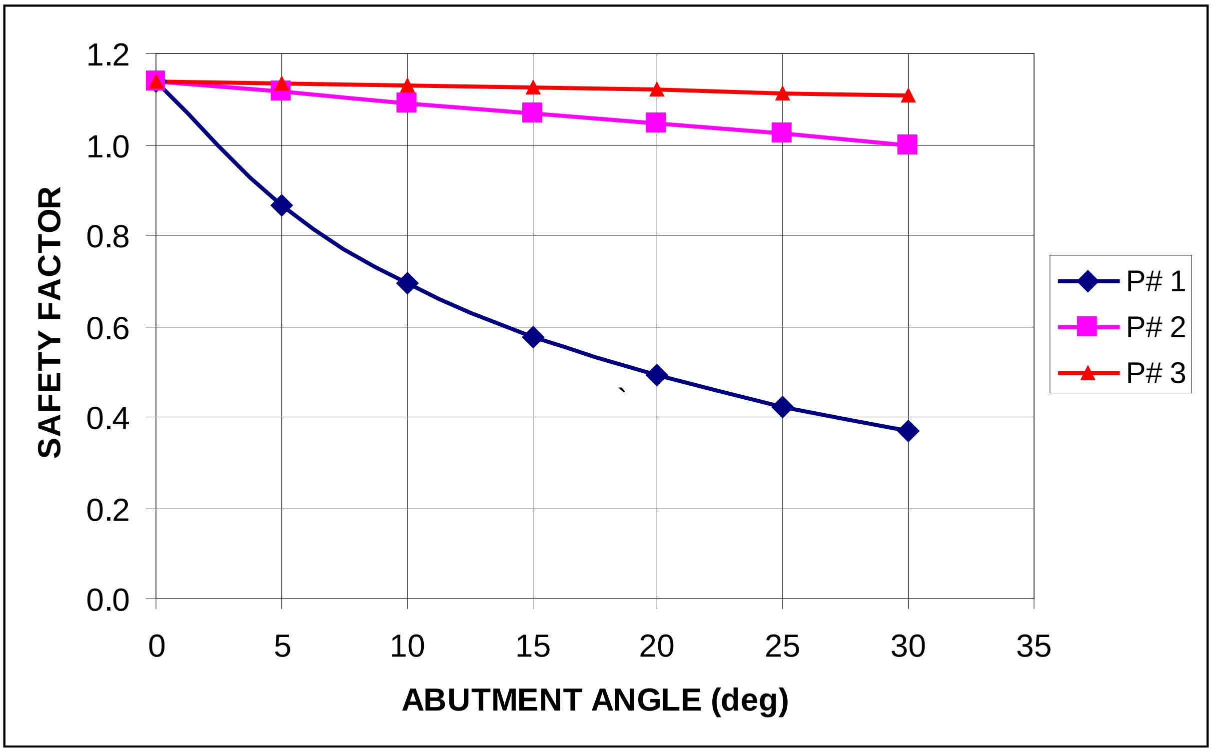


Figure 0–2 Effect of abutment angle on pillar safety factor

Note that the following assumptions and parameters are used in this Figure:

Centre distance (m) = 21
Bord width (m) = 7.2
Mining height (m) = 2.86
Depth to floor (m) = 182.5
Percentage loading of pillar number 1 = 80
Percentage loading of pillar number 2 = 15
Percentage loading of pillar number 3 = 5

Mining method = CM

Density of overburden = 2500 kg/m^3

As can be seen that the Bossjespruit Colliery experiment site dimensions were used in the calculations in producing this Figure. This indicates that the safety factors of first line of small pillars reduced from 1.14 to 0.37 (using Salamon and Munro formula), depending on the abutment angle of the section. To date those pillars are still stable after 8 months. It should also remember that this may well be due to high width to height ratio of pillars.

The importance of the abutment angle raises the question of measurement of it. The abutment angle either can be measured underground, provided there is an access to goaf edge, or it can be measured by monitoring the surface subsidence and plotting it against the relative position of the face.

A spreadsheet program has been included together with all other programs to calculate the surcharge load and safety factors within the AMZ in pillar extraction panels.

Mining risk decision methodology

It is proposed to rationalize the design process of pillar recovery into a two-stage process. The first stage being a pre-feasibility stage in which a rapid assessment is made of all panels being considered for mining, using risk evaluation procedures. The result of the pre-feasibility is a risk ranking of the panels. The second stage of the design would be a full feasibility study of those panels where pillar recovery is most likely to succeed. The flow sheets have therefore been rationalized to fit into this proposed two staged scheme.

1.38 Flow sheets for risk decision methodology

A decision making process for pillar extraction should follow a flow sheet analysis. In general, there are five important evaluations that must be considered. These are:

- Rock engineering evaluation
- Environmental risk evaluation
- Mining evaluation
- Coal beneficiation, and
- Financial evaluation

All these factors have their own constraints and limitations. It is therefore decided to develop flow sheets for the above given evaluations.

- Flow sheet for rock engineering design: This sheet gives a detailed breakdown for the steps that one would go through to carry out a rock engineering assessment and design of single or multiple seam pillar recovery. The flow sheet for rock engineering design is presented in Figure 0–1.
- Environmental flow sheet, which considers surface subsidence, groundwater disturbance, coal fires and land alienation. The flow sheet for environment evaluation is presented in Figure 0–2.

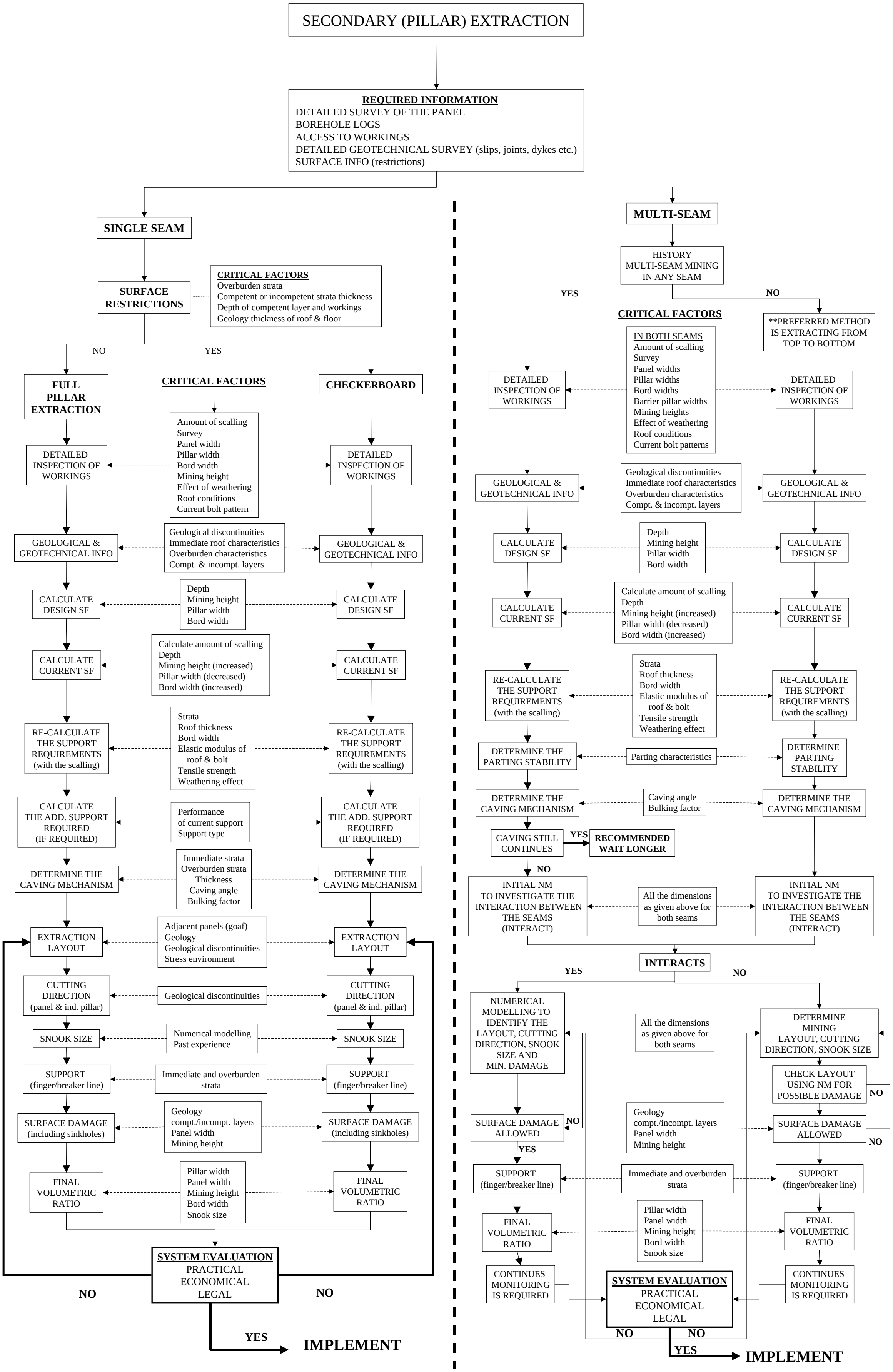


Figure 0–1 Flow sheet for rock engineering design

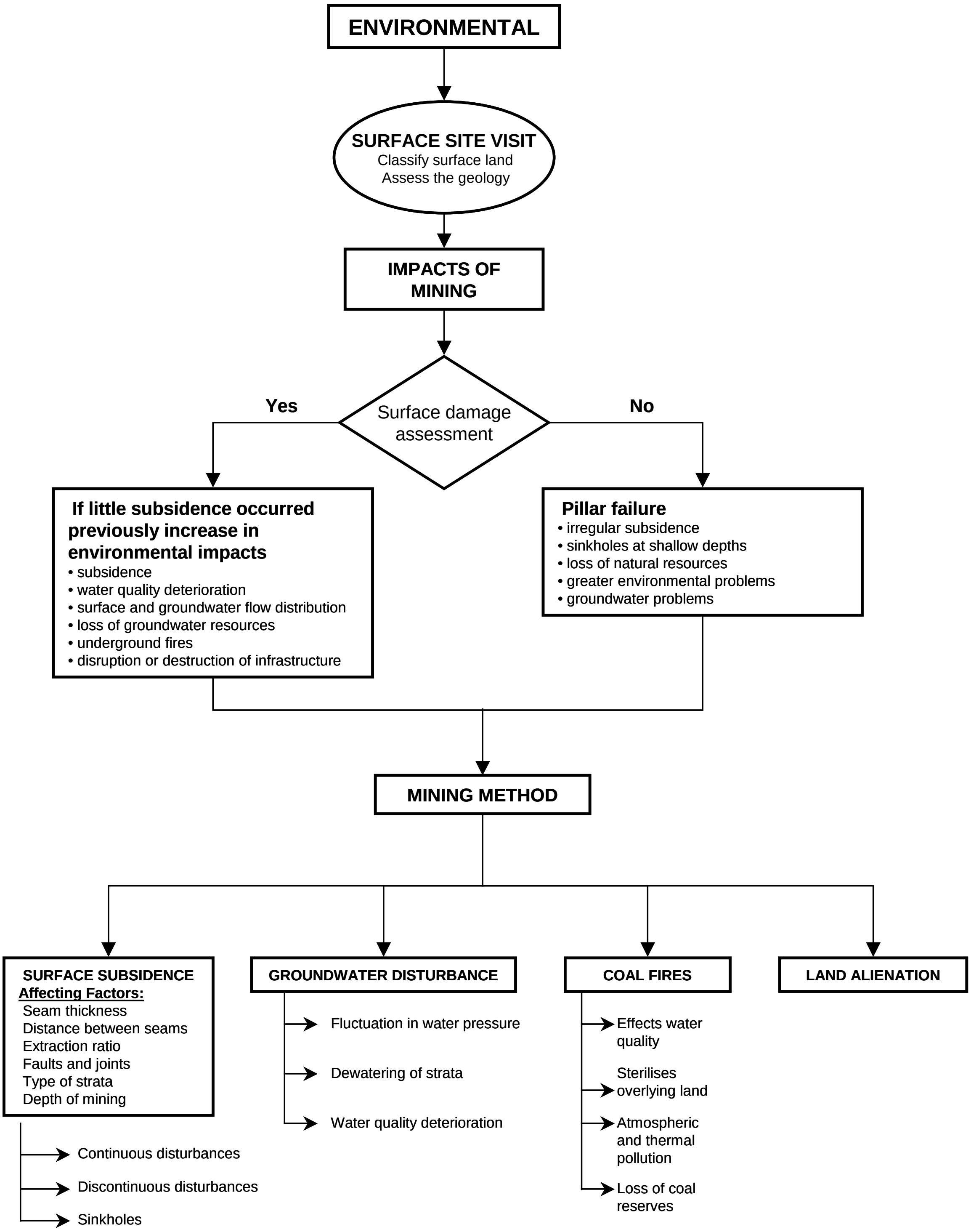


Figure 0–2 Evaluation of environmental factors for pillar extraction

- Mining evaluation. This flow sheet also proposes a two-staged approach and addresses environmental, rock mechanics, ventilation, marketing and cost issues. The flow sheet for mining evaluation is presented in Figure 0–3. It is important to note that as can be seen from this Figure that the mining evaluation is based on two criteria, namely stability and economics. These two criteria however discussed separately. This indicates that if the logistics are appropriate for pillar extraction, which is a function of economics, and the area is safe to extract the pillars, the mining evaluation will indicate “implementation”.

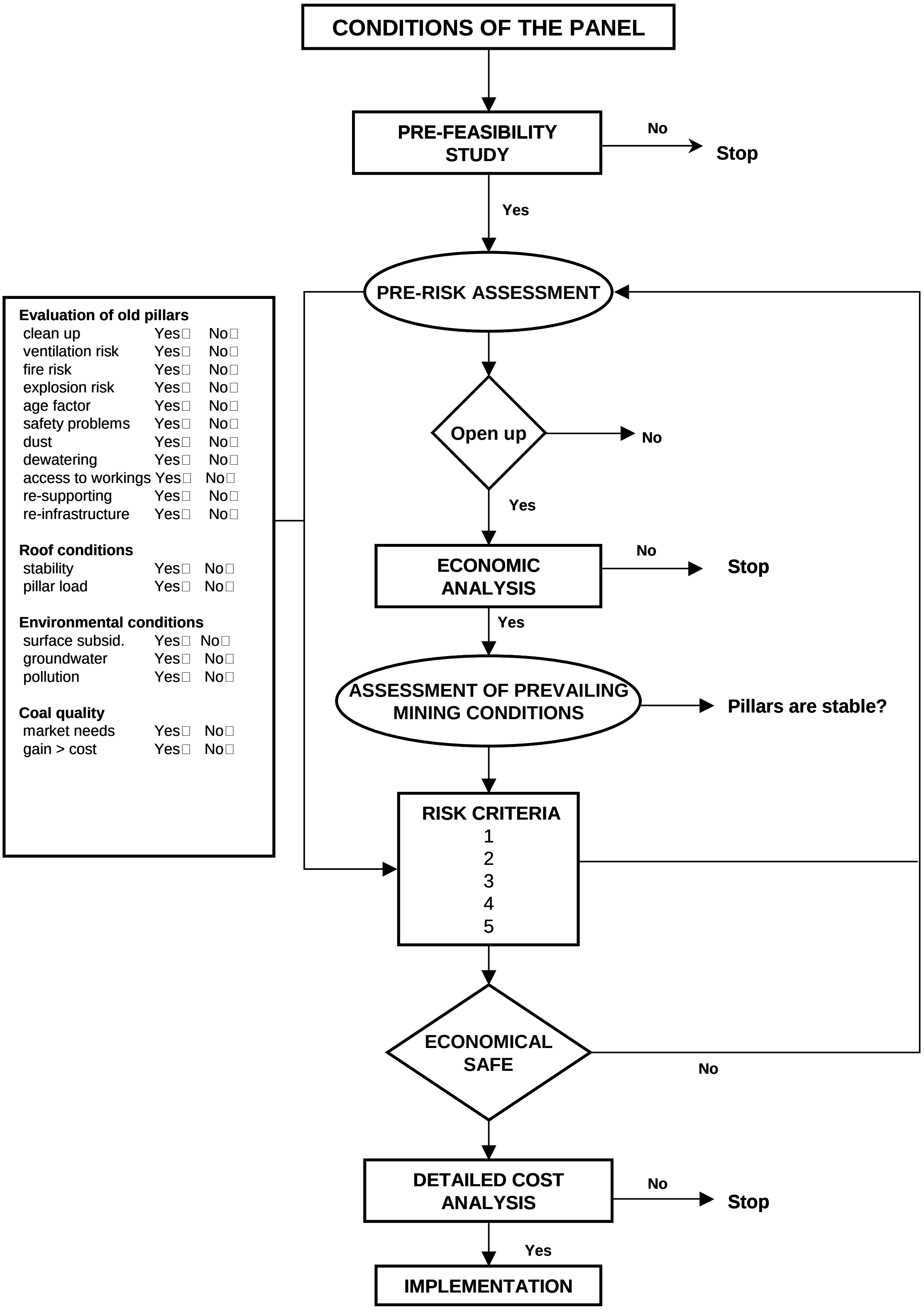


Figure 0–3 Evaluation of mining factors for pillar extraction

- Beneficiation flow sheet considers coal quality and marketing issues and addresses the coal processing plant and associated costs. The flow sheet for beneficiation evaluation is presented in Figure 0–4.

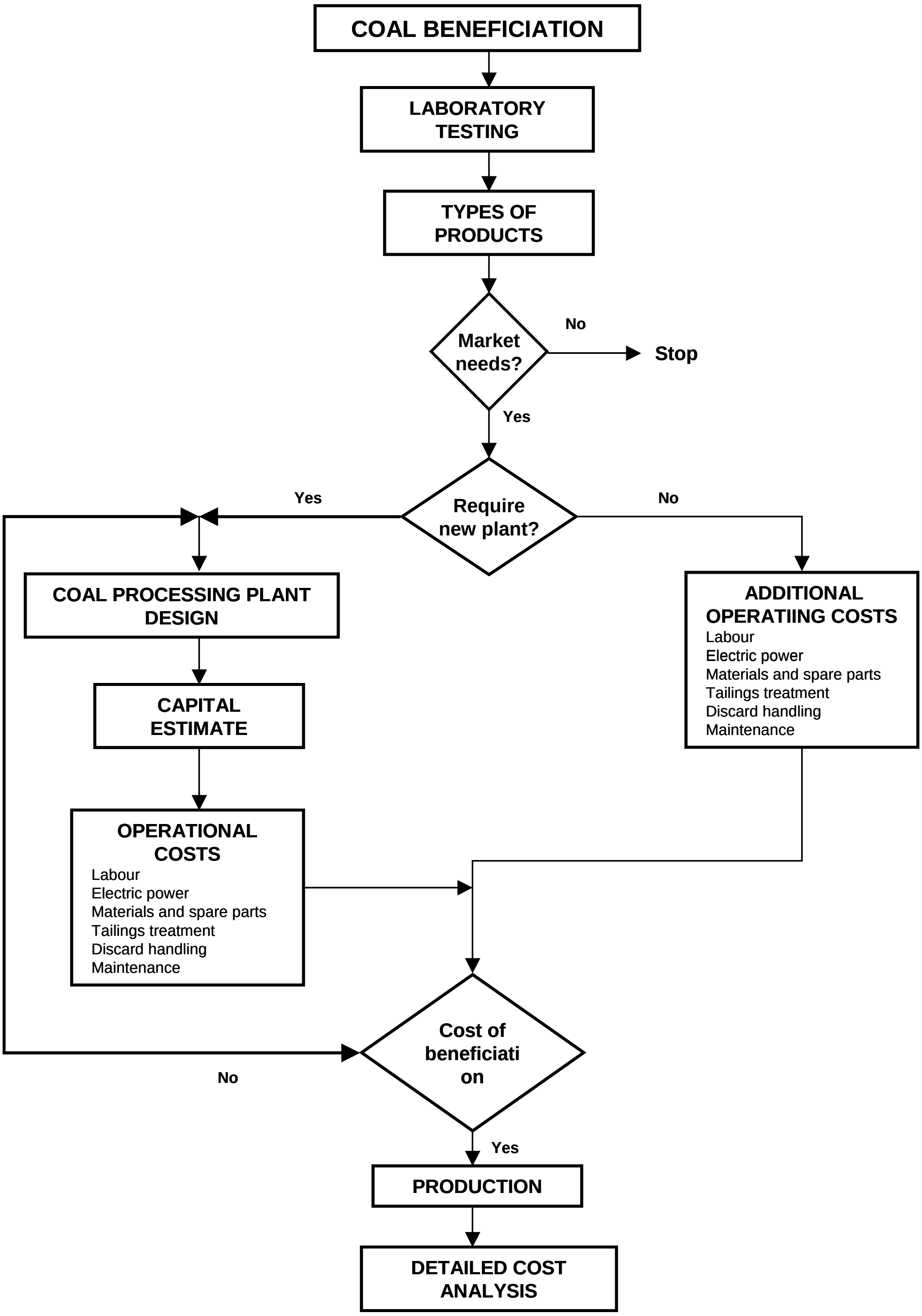


Figure 0–4 Evaluation of coal beneficiation for pillar extraction

- Cost of opening up flow sheet. This flow sheet considers costs associated with obtaining access to the panel. The flow sheet for financial or cost evaluation is presented in Figure 0–5.

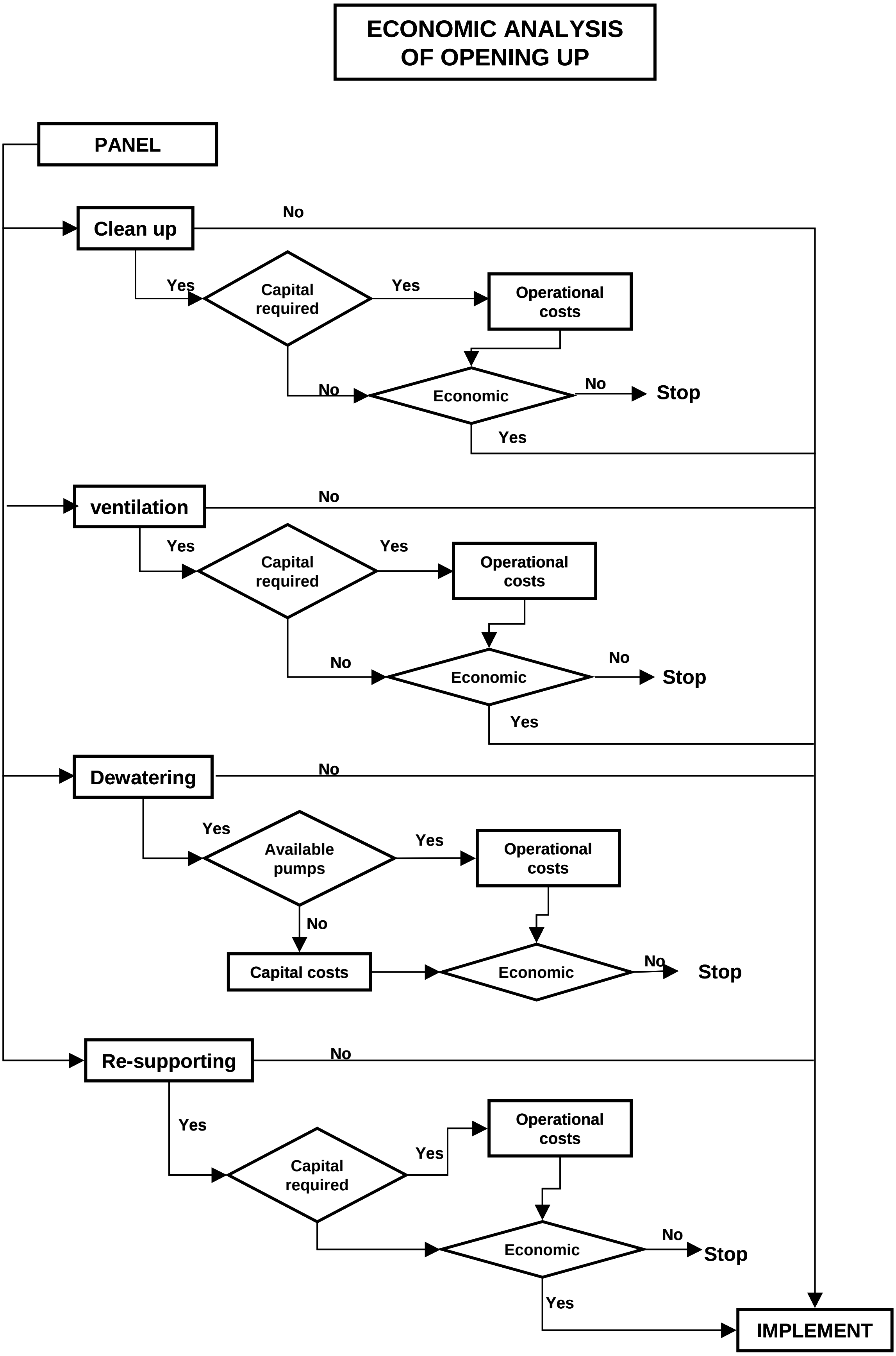


Figure 0–5 Financial evaluation for pillar extraction

Most of the above flow sheets propose data collection, some form of pre-feasibility assessment followed by a more detailed assessment. Costs are an element of all of the flow sheets. From the flow sheets, it is clear that any consideration of pillar recovery mainly involves the stability considerations

These flow sheets also indicate that there is considerable overlap between the different flow sheets. In addition, the connection between the different flow sheets is not clear in terms of an overall investigation. It was therefore decided to developed rationalised flow sheets. The first objective of the rationalisation process was therefore to design an overall flow sheet for the decision process.

1.39 Overall flow sheet for decision process

The overall flow sheet for the decision process to proceed with pillar recovery is presented in Figure 0–9. This flow sheet shows the two stage process, once a decision has been take to consider pillar recovery, a pre-feasibility study is done which ranks the risk of pillar recovery in the panels. This is a rapid risk assessment technique and relies on data currently available. The pre-feasibility study will classify the panels in low, moderate and high risk categories or no-go because of a “fatal flaw”.

All panels with a low to moderate risk will be considered in a full feasibility study, which is the full economical analysis of the panel. If a panel fails the feasibility study, it should be placed in a holding area for consideration at a later stage, when market or other conditions may have changed, allowing the panel to be recovered. Panels having a high risk rating from the pre-feasibility study should also be re-considered after 3 years.

Figure 0–9 also shows that the decision to recover pillars in a panel is taken in two stages. The first decision, to discard a panel, is taken as part of the pre-feasibility, when a panel may be discarded because of a fatal flaw. Fatal flow can be any obvious reason, such as pillar extraction under the Sasol factories. The second decision, whether to proceed or not, is only taken after the feasibility study, and is taken on the basis of the panel being economically viable to mine. A third outcome is possible, where a panel is placed on a holding list, to be re-considered if conditions change. This limitation of the decision process to only two junctions differs from the above given flow sheets in which numerous decision junctions were proposed.

This final flow sheet becomes a pillar recovery management system. It prioritises panels for recovery, eliminates panels that cannot be recovered and ensures that panels that are marginal are reviewed at a later date. It also simplifies the decision process to two opportunities only.

1.40 Detail of pre-feasibility risk assessment

The development of a risk rating system for pre-feasibility study for pillar extraction is presented below. This system has been incorporated into a spreadsheet assisted decision-making tool.

1.40.1 Objectives in developing risk assessment procedure

A pre-feasibility risk assessment should first aim at eliminating panels that cannot be extracted owing to factors that preclude extraction, called “fatal flaws”. The risk associated with extracting the remaining panels should then be determined so that the panels may be ranked according to their suitability for pillar recovery. The risk evaluation system should be simple to calculate and should include all the relevant factors.

1.40.2 Causes of instability

The main causes of instability, that may prevent pillar recovery, were categorized as follows:

- local instability
- regional instability
- multi-seam instability

Each of these main causes was further decomposed into the underlying causes. A total of 38 causing factors were identified, as shown in Figure 0–6. These causes are considered to be root causes for the purpose of the risk rating system. If necessary, they can be broken down further into their constituent components.

The probability of each root cause resulting in the top fault has to be evaluated. A qualitative probability assignment system was used, where the probability is assigned according to the condition or severity of each cause. A preliminary assignment of probabilities was carried out using the relationship shown in Table 0–1.

Table 0–1 Classes for probability of occurrence

Qualitative evaluation	Probability
Certain	1.0 (every time)
Very high	0.1 (one in ten)
High	0.01 (one in a hundred)
Moderate	0.001 (one in a thousand)
Low	0.0001 (one in ten thousand)
Very low	0.00001 (one in hundred thousand)
Extremely low	0.000001 (one in a million)

The relationships between the root causes and their probabilities are presented in Appendix 5, Tables A1 to A5 for the local stability, multiple seam stability and regional stability. These probabilities have been assigned subjectively, using the importance ratings produced as part of COALTECH Task 1.8.2. Further development of some of the root causes may also be necessary. Unnecessary complication of the rating system should be avoided however, since its only objective is to rank panels according to their suitability for pillar recovery.

Directly defining the probabilities as functions of the prevailing conditions greatly simplifies the evaluation procedure, and will allow non-expert users to carry out an assessment. For example, if pillar recovery is to take place at shallow depth, the user only has to state the span to depth ratio, the increased subsidence risk and increased risk of uncontrolled caving is accounted for in the probability assignments.

1.40.3 Risk rating value

The fault tree assumes that any of the causes may occur independently of one another. The causes are not mutually exclusive, and may occur simultaneously. The probability of joint occurrence of the causes is calculated by the expression:

$$p = 1 - (1 - p_1) \bullet (1 - p_2) \bullet (1 - p_3) .... \bullet (1 - p_n)$$

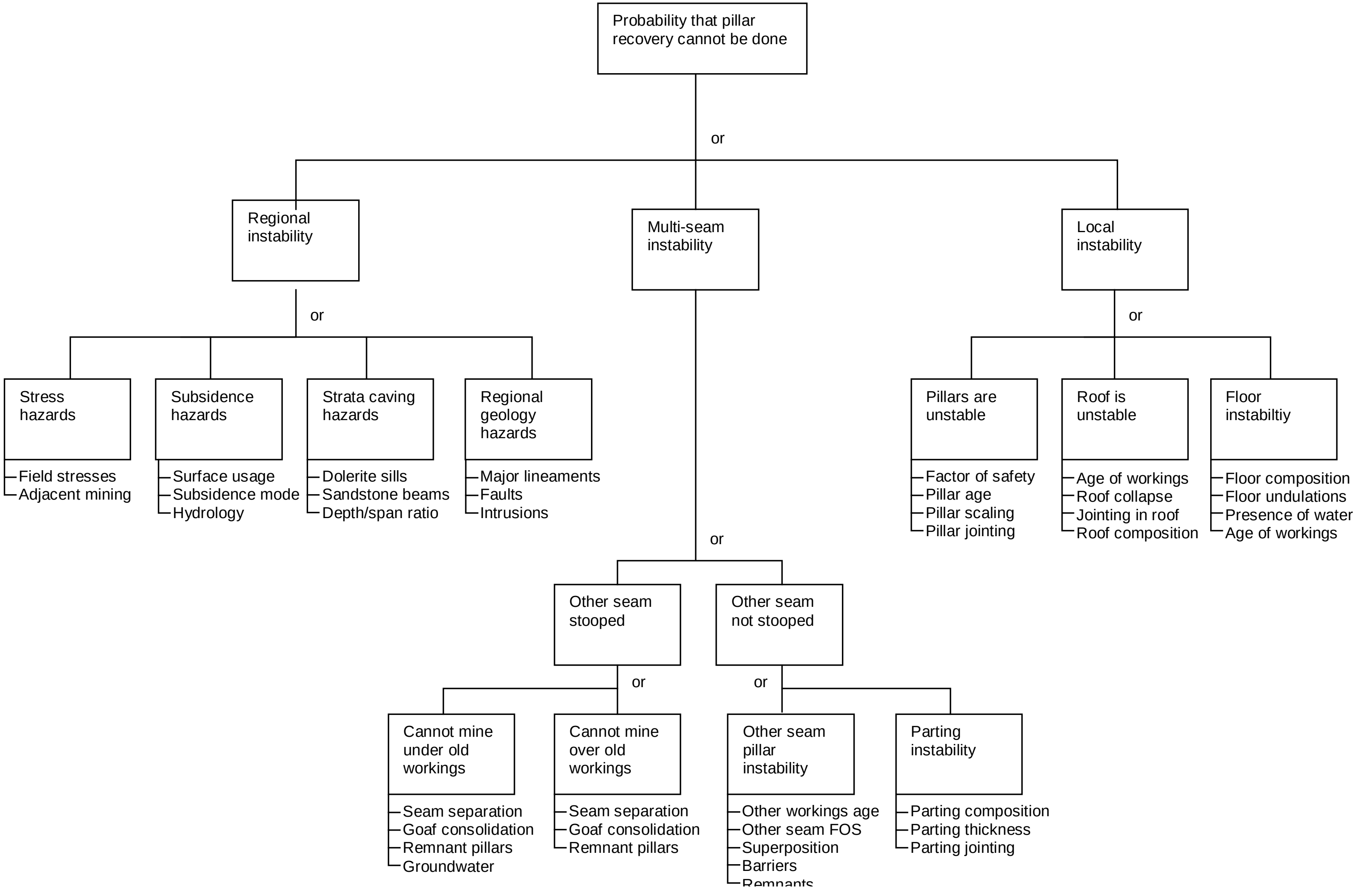


Figure 0–6 Fault tree for stability risk evaluation

where p_i is the probability of occurrence of cause *i.* Once the probability of the top fault has been determined, a risk rating is calculated. Since the objective is to arrive at a risk rating on a scale of 1 to 100, the following expression was used to convert the probabilities to a rating number:

$$R = \left[\frac{6 + \log(p)}{6} \right] \bullet 100$$

The resulting relationship between the probability (*p*) and risk rating (*R*) is presented in Table 0–2.

Table 0–2 Relationship between probability of unsuccessful pillar recovery and risk rating values

Probability (*p*)	**Risk category**	**Risk rating (*R*)**
1.0 (every time)	Cannot be done	100
0.1 (one in ten)	Very risky	83
0.01 (one in a hundred)	Risky	67
0.001 (one in a thousand)	Some risk	50
0.0001 (one in ten thousand)	Low risk	33
0.00001 (one in hundred thousand)	Very low risk	17
0.000001 (one in a million)	Extremely low risk	0

Each category of risk represents an order of magnitude change in the probability of *unsuccessful* pillar recovery. The manner in which the risk rating is calculated, results in approximately a doubling of the probability of failure for every five point increase in the rating.

1.40.4 Development of spreadsheet

In order to test the approach described above, a spreadsheet program was developed which models the fault tree shown in Figure 0–6 and contains the relationships between the causes and assigned probabilities shown in Appendix 5, Tables A1 to A5. To facilitate the rating procedure, a number of data entry forms were created in the spreadsheet, which allow the user to rapidly enter the assessed conditions and calculate the probabilities. The spreadsheet was developed mainly to test the approach proposed here, but may quite easily be developed for general use. The spreadsheet allows users to modify the assigned probabilities and add new causes, if required.

1.40.5 Typical results

The spreadsheet program was used to test a number of hypothetical cases of pillar recovery. The details of two cases are presented here. The first was a panel in a single seam situation and the second a panel in a multi-seam situation. All the basic parameters were the same for the two panels, and may be summarized as follows:

Pillar extraction assumed to occur in a 2.5 m high seam at a depth of 120 m. The panel width was 180 m and the factor of safety of the pillars was between 1.3 and 1.6. The pillars were 20 years old. Geological conditions were assumed to be favourable.

In the case of the multiple seam extraction scenario, it was assumed that the pillars in the second seam were in a similar condition as those in the first seam, and the parting was shale with a thickness of 8m, which is larger than the 6m bord width.

The results of the risk rating system are presented in Appendix 5, Tables A6 and A7 for the single seam and multiple seam cases respectively. The results show that the probability that pillar recovery cannot be done is 0.39 per cent for the multi-seam case, corresponding to a risk rating of 60 and 0.27 per cent for the single seam case, with a risk rating of 57. Both endeavours fall into a risk category of “risky”. The risk of failure is about 44 per cent higher for the multi-seam case compared to the single seam case.

Figure 0–7 and Figure 0–8 show the total and component risks for the two cases in histogram form. The histograms show clearly which components are responsible for the majority of the risk.

A number of test cases were carried out to determine the range of probabilities and risk categories that may be achieved using this system and whether the resulting risk categories were reasonable. The test cases were selected to represent a range of conditions, from a very unfavourable multi-seam situation to an ideal single Seam scenario. The results are summarized briefly in Table 0–3. The results show that the risk rating is expected to lie between values of between about 50 and 90 for typical pillar extraction scenarios. The risk categories vary between “very risky” and “low risk”. These categories appear to describe the risk appropriately.

Table 0–3 Categories for typical pillar extraction scenarios

Brief description	Probability that pillar recovery cannot be done	Risk rating	Risk category
Extraction of >20 year old pillars with low factors of safety in poor condition in multi-seam scenario with thin, weak shale parting under dolerite sill	22%	89	Very risky
Extraction of 15 year old pillars with low factors of safety in favourable geological conditions in multiple Seam conditions.	4.6%	78	Risky
Extraction of 15 year old pillars in single Seam conditions with favourable geological conditions	3.4%	76	Risky
Extraction of 5 year old pillars in single Seam conditions with moderately poor geological conditions	0.54%	62	Some risk
Extraction of 1 year old pillars under ideal conditions	0.09%	49	Low risk

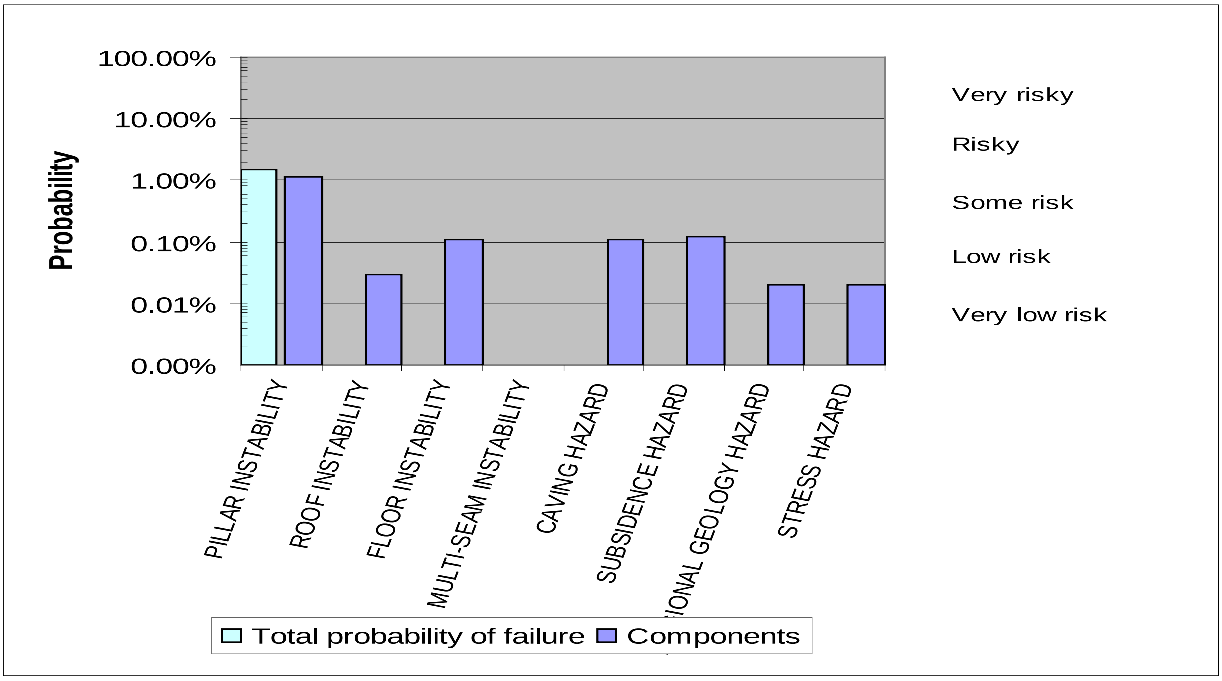


Figure 0–7 Probability histogram –extraction of 20 year old pillars in a single Seam setting

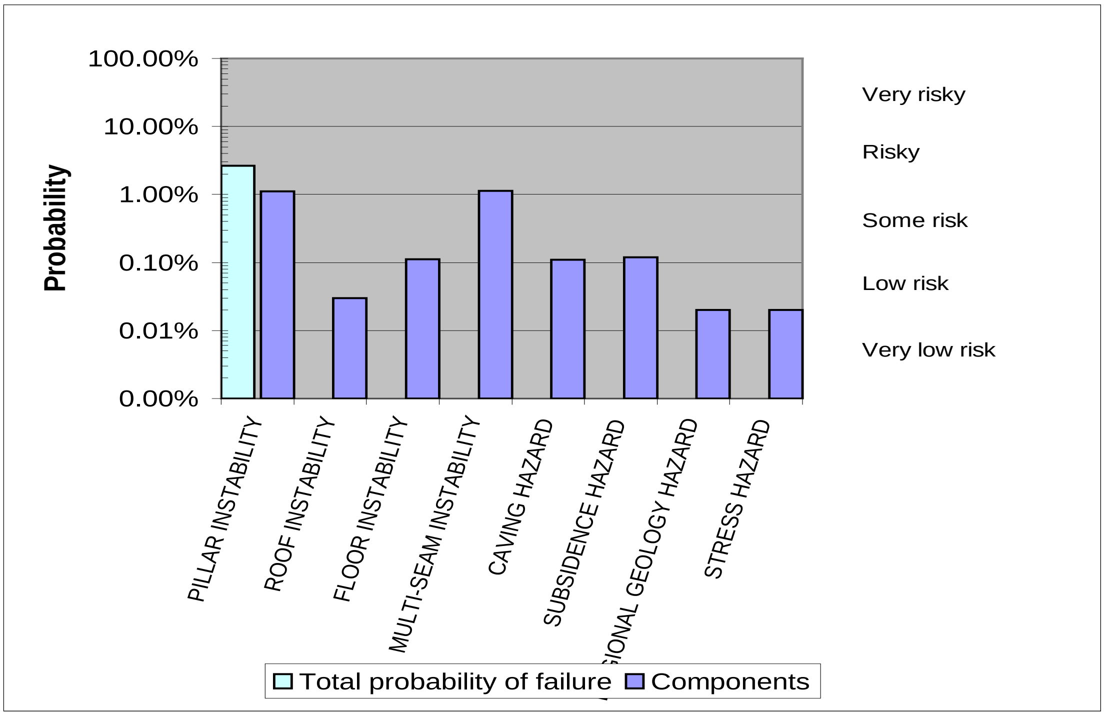


Figure 0–8 Probability histogram –extraction of 20 year old pillars in multi-Seam conditions

1.40.6 Requirement further input and refinement

The development of this risk rating system has been based on a combination of judgement of project staff and the list of factors in the report of Task 1.8.2.

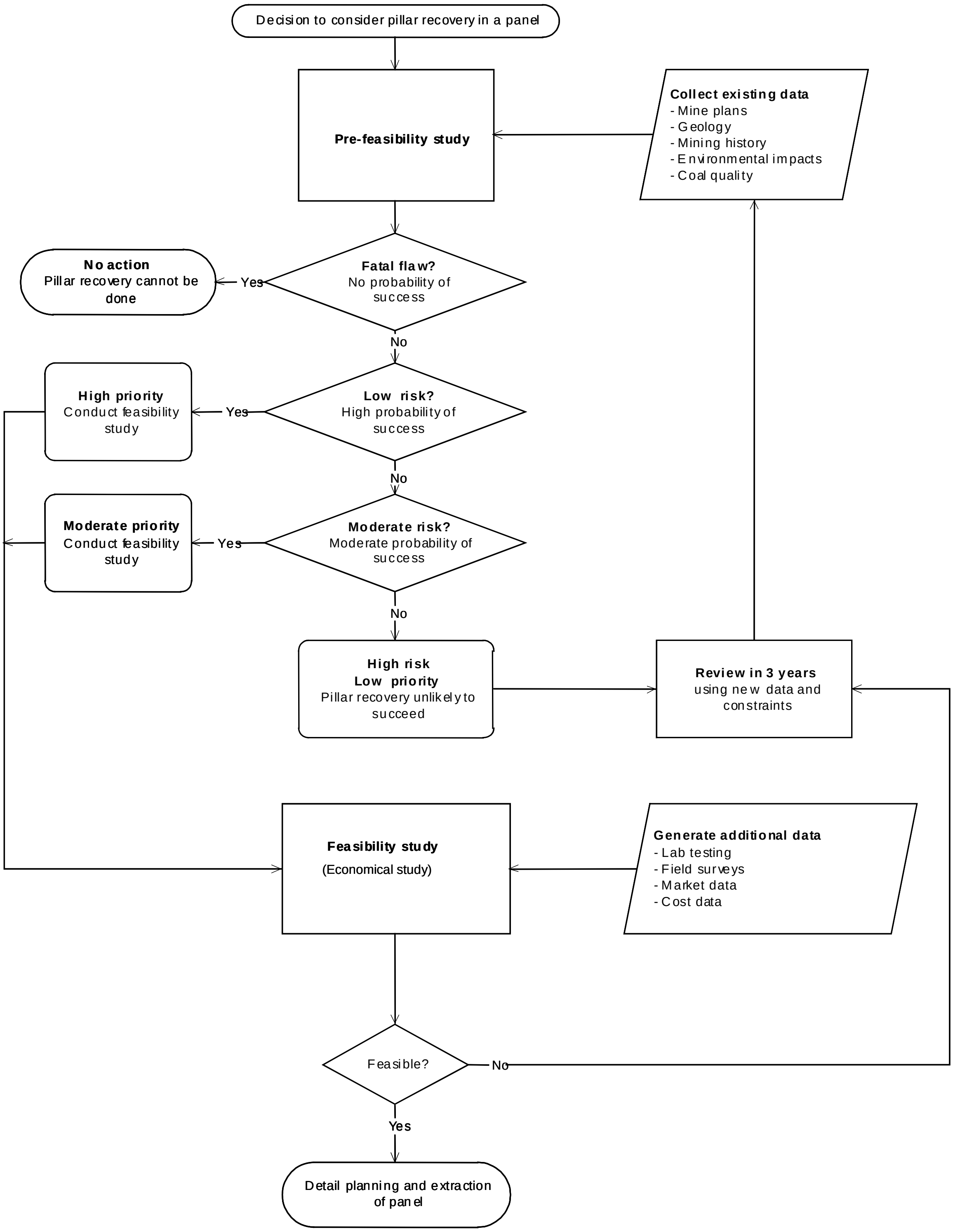


Figure 0–9 Overall flowchart of decision process to proceed with pillar recovery

1.41 Detailed feasibility study

After completing the pre-feasibility study, the low and moderate risk panels will be subject to a detailed analysis as part of the feasibility study. The feasibility study will probably be carried out for a number of panels at a time. The main objective of the feasibility study is to consider all constraints to extracting a panel and producing operational and capital costs so that the economic viability of pillar extraction can be assessed.

The flowchart for the feasibility study is presented in Figure 0–10. The first stage of the feasibility study would be to determine the constraints to pillar recovery in a panel. All the disciplines would contribute to defining what can and cannot be done. Interaction between the disciplines will be necessary, since findings of one discipline will affect other disciplines. Mining and environmental regulations and safety considerations form an important part of the constraints. Figure 0–10 presents the main considerations for each discipline, based on the flow sheets given above. The definition of constraints provides a clear set of specifications that will allow a mining engineer to select an appropriate mining method.

Once the mining method has been selected, it will be possible to calculate the mineable reserve. All the constraints provided by the different disciplines should be considered. The reserve tonnage is required for the economic evaluation and mine design stage.

During the design and costing stage, each discipline is required to carry out designs to a sufficient level of accuracy to allow capital and operating costs to be estimated. The main considerations are listed in Figure 0–10. The final part of the feasibility study is a financial evaluation. The results of the financial evaluation are used to decide whether to proceed with pillar recovery or not, as shown in Figure 0–10.

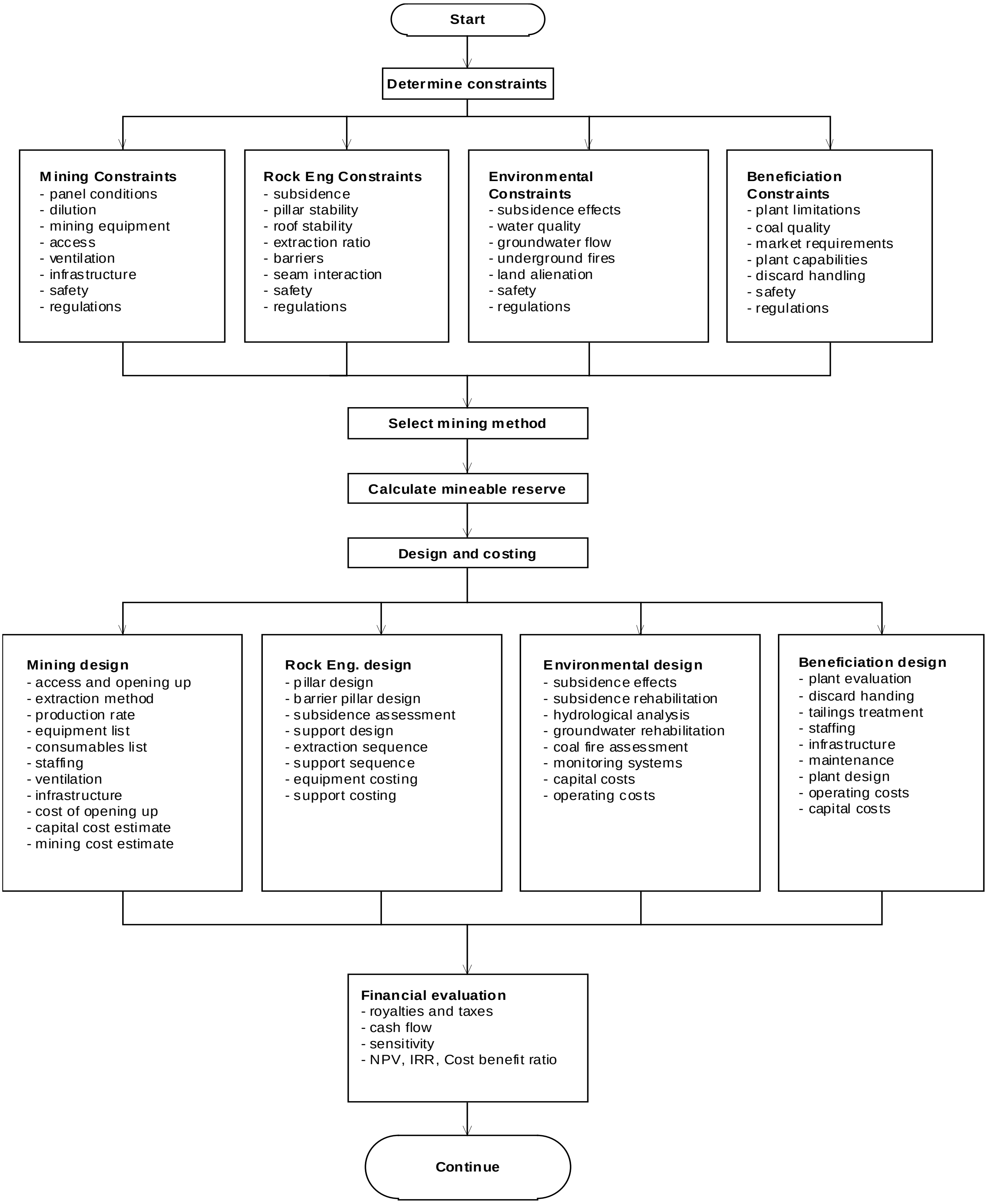


Figure 0–10 **Flowchart for feasibility study**

Mining method decision methodology

1.42 Introduction

The objective of this report is to present a methodology for selecting the best method of pillar recovery for a particular panel that has been mined by bord and pillar methods in the past. The following methods of coal pillar recovery are under consideration in this report:

- Full pillar recovery in which all the pillars are recovered using typical pillar extraction methods;
- Checker-board pillar recovery: in which every second pillar is recovered;
- Pillar splitting: every pillar is split into two smaller pillars by driving a roadway through the pillar;
- Pillar quartering: every pillar is split into four smaller pillars by driving two roadways at right angles through the pillar.

In order to select the best method, the differences between the methods were first listed, under the topics of rock engineering, mining, environmental and beneficiation. Similarities between the methods were ignored, since they would apply equally to all the methods, and would not play a role in selecting a particular method above another.

Once the differences were identified, the requirements for success of the methods were listed, based on the differences. These lists formed the basis for drawing up a checklist that may be used to assess the applicability of each mining method to a particular panel. This process allows unsuitable methods to be eliminated. If more than one mining method survives the checking process, a decision support system may be used to select the best method. The decision support system is based on the Analytical Hierarchy Process developed by Saaty (1994). A spreadsheet has been developed which uses the list of differences between the methods to evaluate their suitability for a given situation.

1.43 Differences between four selected mining methods

The following tables lists the four selected mining methods and the differences between them, in terms of rock engineering, mining, environmental and beneficiation characteristics. The following abbreviations were used: Full pillar extraction (FP), checker-board extraction (CB), pillar splitting (PS) and pillar quartering (PQ). The differences between the methods are used to develop the method selection process.

Table 0–1 Differences between four selected mining methods

	Mining method			
Rock Engineering	**FP**	**CB**	**PS**	**PQ**
Pillar safety factor	Adequate safety factor required to accommodate high abutment loading	Abutment loading not as severe as for FP	Abutment loading not as severe as for FP	Abutment loading higher than for CB and PS but lower than FP
Snook factor of safety	Snooks must crush in short term, need very low FOS	Remaining pillars must have FOS < 1 (?) so that they yield in medium term	Snooks (ribs) must have FOS between 0.5 and 0.7 (?) to ensure controlled yield in medium term	Snooks (ribs) must have FOS between 9.3 and 0.5 (?) to ensure controlled yield in medium term
Snook failure	Rapid failure immediately after pulling breakerline supports desired	Remaining pillars must fail in controlled manner over medium term	Snooks (ribs) must fail in controlled manner in medium term	Snooks must fail in controlled manner in short term
Loading system stiffness	Stiffness requirement not as stringent, barrier pillars should be adequate	Requirement for high stiffness so that pillars yield in controlled manner	Requirement for high stiffness so that pillars yield in controlled manner	Stringent requirement for adequate stiffness so that snooks yield in controlled manner
Caving of upper strata	Controlled caving needed, presence of dolerite sills or thick sandstone layers unfavourable	Caving not expected to occur, caving behaviour not important	Caving not expected to occur, caving behaviour not important	Controlled caving needed, presence of dolerite sills or thick sandstone layers unfavourable
Goafing of immediate roof	Immediate roof must goaf in controlled manner	Goafing not required	Goafing not required	Goafing not required
Multiseam: stability of over & underlying workings	Large abutment pressure caused which may overload adjacent pillars	Abutment stresses much lower than FP	Abutment stresses much lower than FP	Abutment stresses lower than with FP but higher than CB and PS
Multiseam: Stability of Seam parting	High abutment loading requires stable Seam parting and superposition	Lower abutment stresses places lower demand on Seam parting and superposition	Lower abutment stresses places lower demand on Seam parting and	High abutment loading requires stable Seam parting and superposition
Strength of	Lower strength	High strength	High strength	High strength

roof strata	favourable for regular goafing	required to span across removed pillar	not required but advantageous	not required but advantageous
Surface subsidence	Subsidence magnitude greatest of the four methods	Subsidence least of the four methods, sinkhole formation possible at shallow depth	Subsidence moderate compared to FP and CB	Subsidence moderate compared to FP and CB

Mining	**FP**	**CB**	**PS**	**PQ**
Recovery	High recovery of in-panel pillars possible (80%)	Recovery of 50% of remaining pillars	Recovery between 50% and 80% (?) depending on splitting width	Recovery of 80% possible
Breakerlines	Installation and removal of breakerlines & fingerlines required	Breaker and fingerlines not needed	Breaker and fingerlines not needed	Breaker and fingerlines may be needed
Mining cost	Highest cost method	Lower cost and recovery	Lower cost and recovery	Intermediate cost and recovery
Direction of pillar splitting	May have to split pillars in particular direction to control roof stability	Direction of splitting not as important as FP	Direction of splitting not as important as FP	May have to split pillars in particular direction to control roof stability
Training and experience	Mining team needs high skill levels and experience to control goafing	Skill levels not as high as FP	Skill levels not as high as FP	High skill levels and experience with yielding system
Safety of employees	Greater hazards associated with goaf control	No goafing but high hazards if roof unstable over large spans	Lower roof fall hazards	High hazards owing to yielding system
Production rate	High but erratic	Lowest due to moving around	Higher than CB, but still low	Slightly higher than PS

Environmental	**FP**	**CB**	**PS**	**PQ**
Environmental disturbance owing to subsidence	Most severe disturbance owing to maximum subsidence	Lesser disturbance owing to less severe subsidence	Lesser disturbance owing to less severe subsidence	Subsidence not as severe as FP but more than CB and PS
Spontaneous combustion	Crushing of snooks may cause	Pillars may yield in longer term, after panel is	Pillars may yield in longer term, after panel is	Crushing of snooks may cause

	spontaneous combustion during operations	sealed, lesser risk of spontaneous combustion	sealed, lesser risk of spontaneous combustion	spontaneous combustion during operations
Groundwater – extent of damage can sometimes be controlled by panel design	Damage to ground-water table certain in short term	Possible damage to groundwater table in long term	Possible damage to water table in medium to long term	Damage to ground water table certain over short to medium term
Beneficiation	**FP**	**CB**	**PS**	**PQ**
Dilution	Increased dilution when mining adjacent to goaf	Low dilution owing to absence of goaf	Low dilution owing to absence of goaf	Low dilution provided goafing is avoided near extraction line

1.44 Requirements for successful application of methods

The table below lists the factors that are required for the successful application of the four pillar recovery techniques. The requirements that are equal for all the methods are not listed. The importance or impact for each method is indicated as follows: High (H), moderate (M), low (L) and none (N). The list may be used to assist in determining whether a method is suitable for application in a particular panel. The table shows that full pillar recovery and pillar quartering place much higher demands than checker-board or pillar splitting. This implies, in a general sense, that the requirements of checker-board and pillar splitting method will be satisfied more readily than the requirements of full pillar recovery and pillar quartering.

Table 0–2 List of requirements for successful application of methods and their relative importance

Category	**Requirement**	**Reason**	**Importance/Impact on metod**			
			FP	**CB**	**PS**	**PQ**
Rock engineering	Adequate safety factor of pillars in abutment zone	High abutment loading of pillars as extraction line advances could cause a pillar run	H	M	M	H
	Adequate safety factor of snooks or remaining pillars	Pillars or snooks that remain after secondary extraction, eg. when pillar splittting, must have adequate strength to remain stable for a sufficient length of time	L	H	H	H
	Controlled caving of upper strata ensured	Caving must occur in a controlled manner so that pillars are not overloaded. Dolerite sills, strong strata or small spans between barriers may result in intermittent caving.	H	N	N	L
	Surface subsidence acceptable	Full pillar recovery will result in most severe surface subsidence of the methods, the subsidence edge will be abrupt	H	L	L	M
	Controlled goafing of immediate roof strata	Immediate roof strata should cave readily but not overrun breakerline supports	H	N	N	L
	Adequate stability of over/underlying Seams	If other Seams have been mined they may be severely affected by abutment loading as pillars are extracted. Seam separation and pillar centers must be evaluated	H	L	L	M
	Adequate stability of Seam partings	If other Seams have been mined the parting is required to remain stable. Parting composition and thickness	H	M	M	H

		must be evaluated				
	System stiffness adequate	If yielding pillars are left the loading system stiffness must be adequate to ensure non-violent yield. This is affected by barrier spacing.	N	M	M	H
	Adequate roof strength	Large spans are created when pillars are removed, spans must remain stable during operations	M	H	M	M
	Controlled yield of remaining pillars over long term	Over loaded remaining pillars will ultimately fail, they should do so in a controlled manner. The width to height ratio of remaining pillars	N	M	M	H
Mining	Ability to provide breakerline/ fingerline supports	Roofbolt or timber breakerlines are required, Seam height or roof condition may preclude installing breakerlines	H	N	N	L
	Ability to control direction of pillar splitting	Pillar splitting direction relative to geological structures and field stress impacts the local roof stability	H	L	L	M
	Training and experience	Pillar extraction requires special skills and experience with local conditions. Miners need to be familiar with roof behaviour and goafing characteristics	H	M	L	H
	Safety of employees	Safety is compromised if employees work near goaf	H	N	N	M
Environmental	Groundwater disturbance	Groundwater is disturbed by creation of cave fractures and subsidence	H	M	M	H
	Subsidence limitations	The severity of subsidence varies according to the amount of coal extracted. The surface environment may be affected by subsidence.	H	L	L	M
	Spontaneous combustion	Formation of snooks and crushing coal may result in spontaneous combustion	H	L	L	H
Beneficiation	Ability to accommodate dilution	Mining adjacent to goaf results in higher quantity of waste rock in coal	H	N	N	L

1.45 Checklist of requirements against panel constraints

When deciding on a mining method for a particular panel, the first objective will be to determine whether the constraints associated with the panel eliminate any of the methods. Before the checks can be carried out, data regarding the panel must be collected and several basic calculations must be carried out. Table 0–3 shows the factors that must be considered, a space has been left open to fill in the constraint posed by the panel and four columns to indicate whether the different methods satisfy the constraints. An example of a hypothetical panel assessment is presented as Table 0–4.

The example shows that full pillar recovery and pillar quartering are both eliminated, since they do not satisfy a number of the constraints imposed by the panel. This first stage elimination will reduce the number of options that need to be considered during the method selection process.

The data collection and studies required to evaluate the different mining methods are summarized in Table 0–5. For example, pillar and snook safety factors, roof stability, mining costs and environmental assessments have to be done to determine what the constraints are. The technology to determine some of the answers that the studies have to provide are not well developed, such as deciding how well a roof stratum will goaf. Further research into using roof rating systems may be required. Several of the other aspects will benefit by further research.

Table 0–3 Checklist to determine if mining methods are eliminated by panel constraints

Category	**Requirement**	**Panel constraint**	**Does method satisfy constraint?**			
			FP	**CB**	**PS**	**PQ**
Rock Eng	Surface subsidence					
	Middling stability					
	Pillar superposition					
	Factor of safety of pillars in other Seam					
	Factor of safety of snooks					
	Factor of safety of pillars in abutment zone					
	Controlled goafing of immediate roof					
	Controlled caving of upper strata					
	System stiffness adequate					
	Roof strength adequate					
	Long term yield of pillars					
Mining	Coal recovery requiremnt					
	Ability to provide breakerlines					
	Acceptable mining cost					
	Control direction of pillar splitting					
	Training and experience					
	Safety next to goaf satisfactory					
Environ-	Groundwater					

mental	disturbance					
	Subsidence effect on environment					
	Spontaneous combustion					
Beneficiation	Accommodate dilution					

Table 0–4 Example of panel and mining method assessment

Category	**Requirement**	**Panel constraint**	**Does method satisfy constraint?**			
			FP	**CB**	**PS**	**PQ**
Rock Eng.	Surface subsidence	*Must be < 1m*	*N*	*Y*	*Y*	*N*
	Middling stability	*Middling 4.5m*	*Y*	*Y*	*Y*	*Y*
	Pillar superposition	*Pillar centres 15m*	*N*	*Y*	*Y*	*N*
	Factor of safety of pillars in other Seam	*FOS 1.66*	*Y*	*Y*	*Y*	*Y*
	Factor of safety of snooks	*Seam height 2.1m pillars 9m*	-	*Y*	*Y*	*Y*
	Factor of safety of pillars in abutment zone	*Current FOS 1.5*	*N*	*Y*	*Y*	*Y*
	Controlled goafing of immediate roof	*2m thick sandstone*	*N*	-	-	*N*
	Controlled caving of upper strata	*No dolerite sills or thick sandstone beams*	*Y*	-	-	*Y*
	System stiffness adequate	*15m wide barriers 120m apart*	*Y*	*Y*	*Y*	*N*
	Roof strength adequate	*2m thick sandstone*	*Y*	*Y*	*Y*	*Y*
	Long term yield of pillars	*High system stiffness*	-	*Y*	*Y*	*Y*
Mining	Ability to provide breakerlines	*Seam height 2.1m OK*	*Y*	*Y*	*Y*	*Y*
	Control direction of pillar splitting	*Major joints run NW/SE can split perpendicular to this direction*	*Y*	*Y*	*Y*	*Y*
	Recovery acceptable	*Must recover more than 50% of pillars to be viable*	*Y*	*Y*	*Y*	*Y*
	Mining cost acceptable	*Not cost sensitive*	*Y*	*Y*	*Y*	*Y*
	Training and experience	*Have teams experienced in pillar extraction*	*Y*	*Y*	*Y*	*Y*
	Safety next to goaf satisfactory	*Goaf will break in large slabs – safety an issue*	*N*	*Y*	*Y*	*N*
Environmental	Groundwater disturbance	*No problems foreseen*	-	-	-	-
	Subsidence effect on environment	*Erosion if subsidence exceeds 1m*	*N*	*Y*	*Y*	*N*
	Spontaneous combustion	*Coal relatively inert*	*Y*	*Y*	*Y*	*Y*
Beneficiation	Accommodate dilution	*No washing plant – dilution must be limited*	*Y*	*Y*	*Y*	*Y*

Table 0–5 Studies and data collection required to evaluate method requirements

Category	**Requirement**	**Evaluation method**
Rock Eng.	Surface subsidence	Empirical subsidence prediction methods of Schumann and Wagner or use local records if available
	Middling stability	Salamon's guidelines, or use local experience if available
	Pillar superposition	Salamon's guidelines, or use local experience if available
	Factor of safety of pillars in other Seam	Salamon's guidelines, or use local experience if available
	Factor of safety of snooks	Numerical modelling or empirical guidelines based on local experience
	Factor of safety of pillars in abutment zone	Numerical modelling and pillar strength equations
	Controlled goafing of immediate roof	Roof stability index (?) Coal Mine Roof Rating
	Controlled caving of upper strata	Geological assessment, dolerite sill evaluation and previous experience
	System stiffness adequate	Numerical modelling, possibly, Ryder's BEPIL program
	Roof strength adequate for large spans	Geological assessment of roof laminations, CMRR and previous experience
	Long term yield of pillars	Stiffness assessment and consideration of w:h ratio of pillar. Numerical models.
Mining	Ability to provide breakerlines	Consideration of practicality of installing breakerlines, mechanical breakers, bolts etc.
	Control direction of pillar splitting	Consideration of ability to split pillars in a favourable direction
	Training and experience	Consideration of ability of mining team, past experience and whether training can be done.
	Safety next to goaf satisfactory	Consideration of likely predictability of goaf and goaf overruns, whether it can be controlled
Environ-mental	Groundwater disturbance	Groundwater investigation
	Subsidence effect on environment	Environmental impact assessment
	Spontaneous combustion	Coal combustion testing
Beneficiation	Accommodate dilution	Consideration of beneficiation process, washing plant and market requirements

1.46 Decision support system to select best mining method

The mining methods that survive the initial screening should be subject to a selection process that will indicate which is the best method. The application of the Analytical Hierarchy Process (AHP), as developed by Saaty (1994), has been used as a basis for the selection process. The AHP process was developed as part of the United States Arms Control and Disarmament Agency in the nineteen sixties to facilitate decision making when one is faced with complex interrelated problems. The AHP process is simple in its fundamental premise that only two alternatives are compared at a time against a given criterion. The process is repeated for all alternatives and all criteria. The judgements are summed to identify the best alternative.

1.47 Outline of decision process

The outline of the AHP process may be summarized as shown in Figure 0–1. The goal of finding the best method is set. Below the goal, the criteria are subdivided into disciplines. The relative weighting of each criterion is determined using pairwise comparisons. Finally the alternative methods are evaluated, using pairwise comparisons against each of the criteria. The outcomes are manipulated mathematically to provide the best solution.

The method has been programmed into a spreadsheet, so that users do not need to carry out the calculations themselves. The spreadsheet program is specifically designed to evaluate the problem of mining method selection, using the criteria listed above.

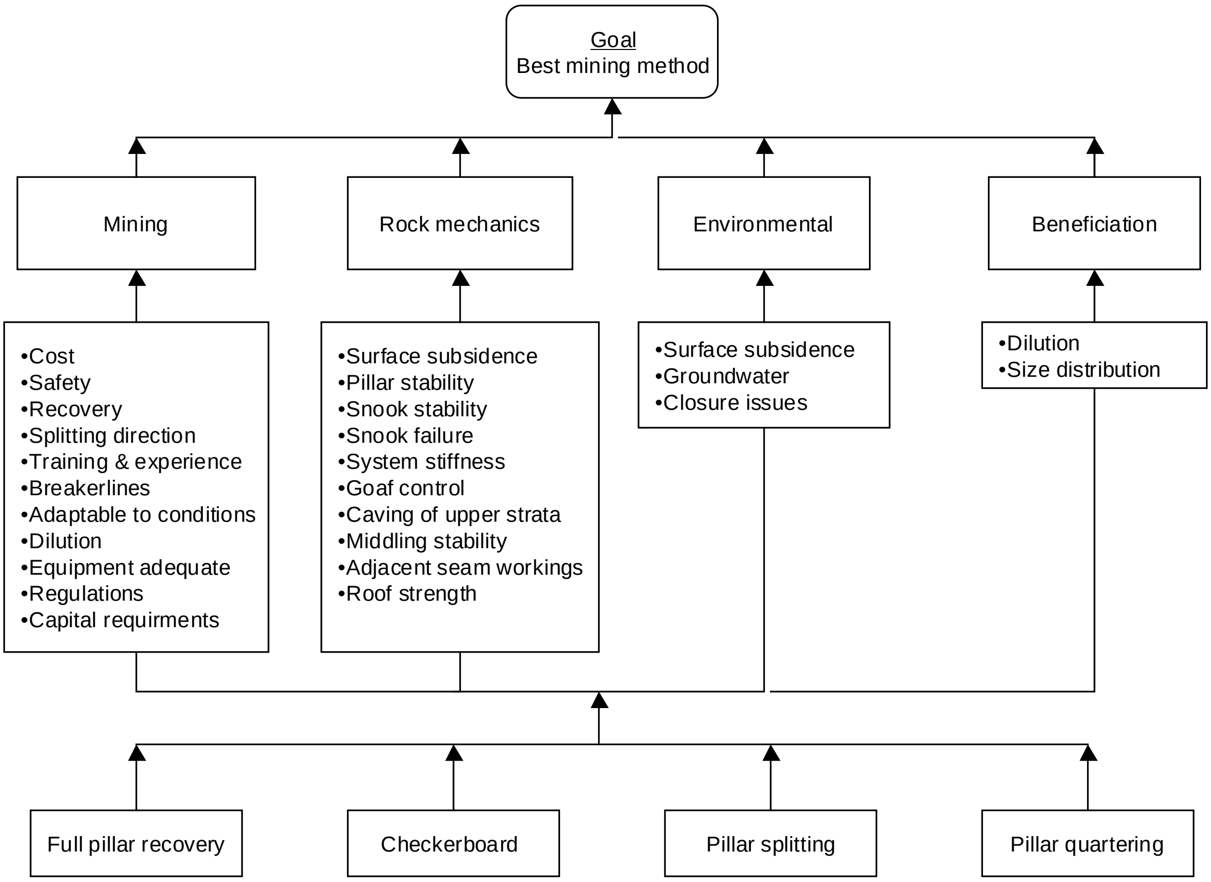


Figure 0–1 Outline of analytical hierarchy process for selecting best method

1.48 Example of application of AHP spreadsheet to evaluate suitability of mining methods

As an example, the AHP spreadsheet was used to evaluate the four mining methods under consideration for two hypothetical panels. The first panel (A) is a single Seam extraction with the following general limitations:

- The mine employees are accustomed to pillar splitting but have never done full pillar recovery before.
- The immediate roof is strong and there is concern that it will not goaf readily, but is expected to stand up over extended spans.
- Previous pillar extraction trials showed that snooks tended to fail violently and unexpectedly.
- A dolerite sill in the upper strata will fail intermittently, causing high abutment stresses.
- Surface subsidence of up to 2m is tolerable.
- The mine has a washing plant and dilution of the coal is not a major concern.

The main concerns are therefore related to panel stability issues, followed by operational concerns related to the lack of experience of the employees in three of the mining methods. The environmental and beneficiation issues are lesser concerns.

The AHP spreadsheet was used first to rate the relative importance of the four main criteria for selecting a mining method. The results are presented in Figure 0–2, which shows the relative importance of the criteria after rating their relative importance using the AHP process. The importance of stability and operational criteria are clearly highlighted. These relative priorities are used to weight the importance of the sub-criteria associated with each criterion.

After rating the importance of the main criteria, all the sub criteria were assessed. During this assessment the limitations imposed by the panel are borne in mind when assigning priorities. The results are summarized in the figures on the next few pages. The results are specific for the panel and other evaluators will produce a different set of priorities. The priorities assigned by several knowledgeable persons may be combined in the spreadsheet.

Figure 0–3 shows that mining cost, safety and the ability to satisfy regulations are the main operational concerns, followed by concern over the training and experience of the mining crew. The results in Figure 0–4 show that roof stability, failure of snooks, stability of pillars at the extraction line and goaf control are the main stability concerns.

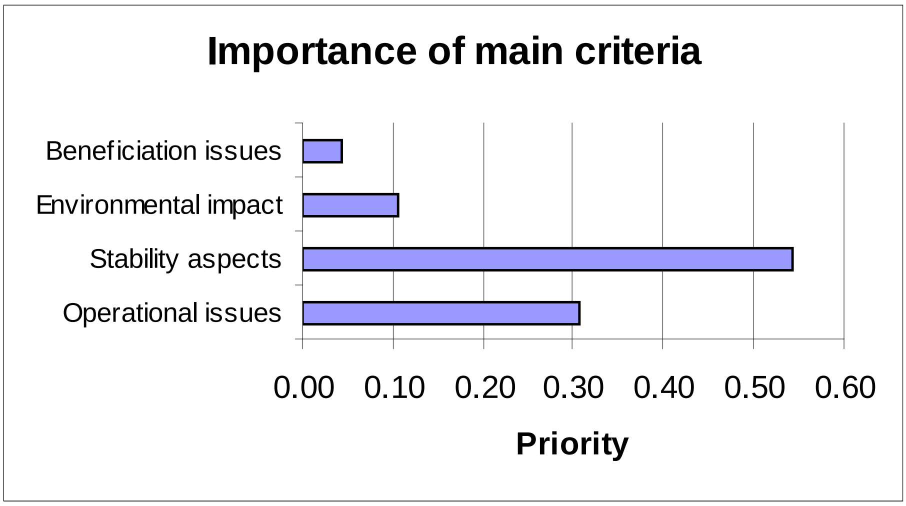


Figure 0–2 Relative importance of criteria for hypothetical Panel A

The relative priority of the environmental and beneficiation concerns are shown in Figure 0–5.

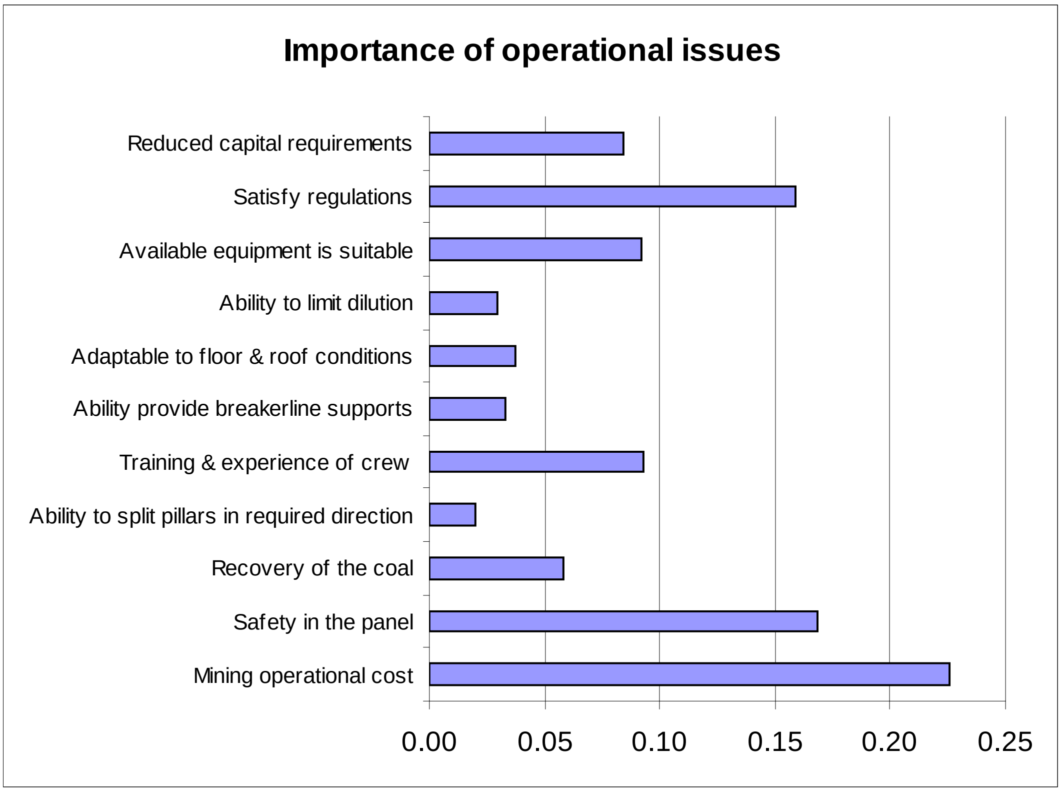


Figure 0–3 Relative importance of operational issues for hypothetical panel A

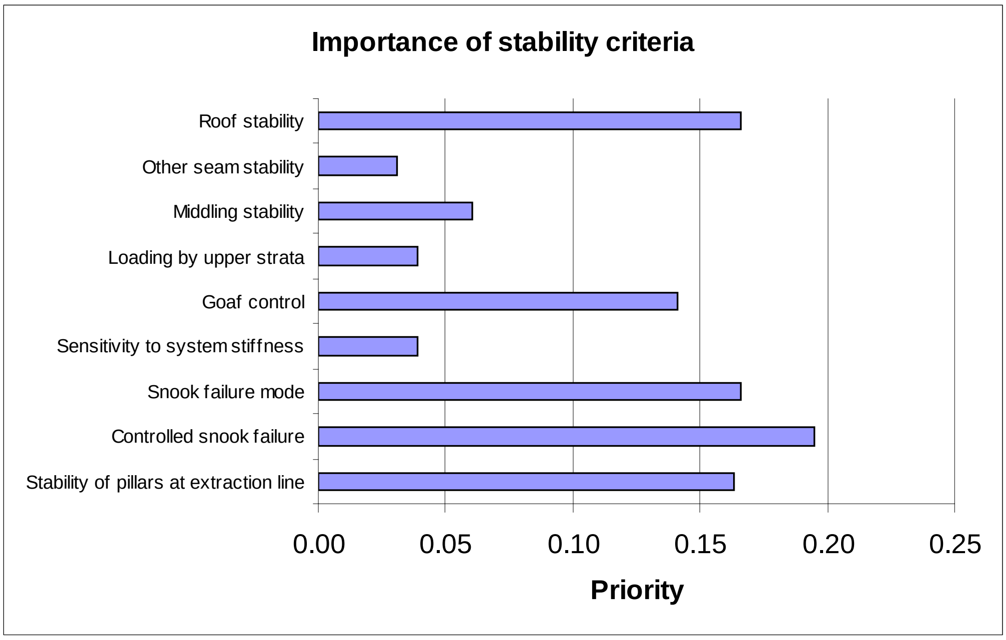


Figure 0–4 Relative importance of stability considerations for hypothetical panel A

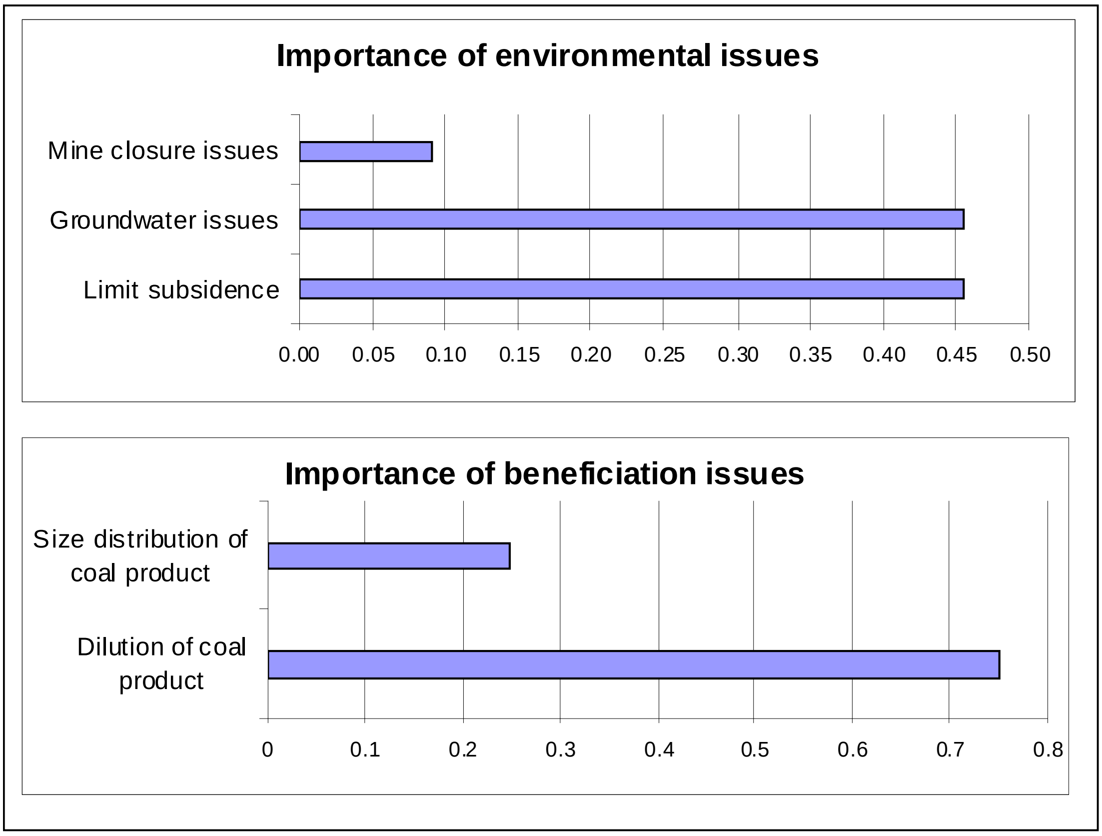


Figure 0–5 Relative importance of environmental and beneficiation issues for hypothetical Panel A

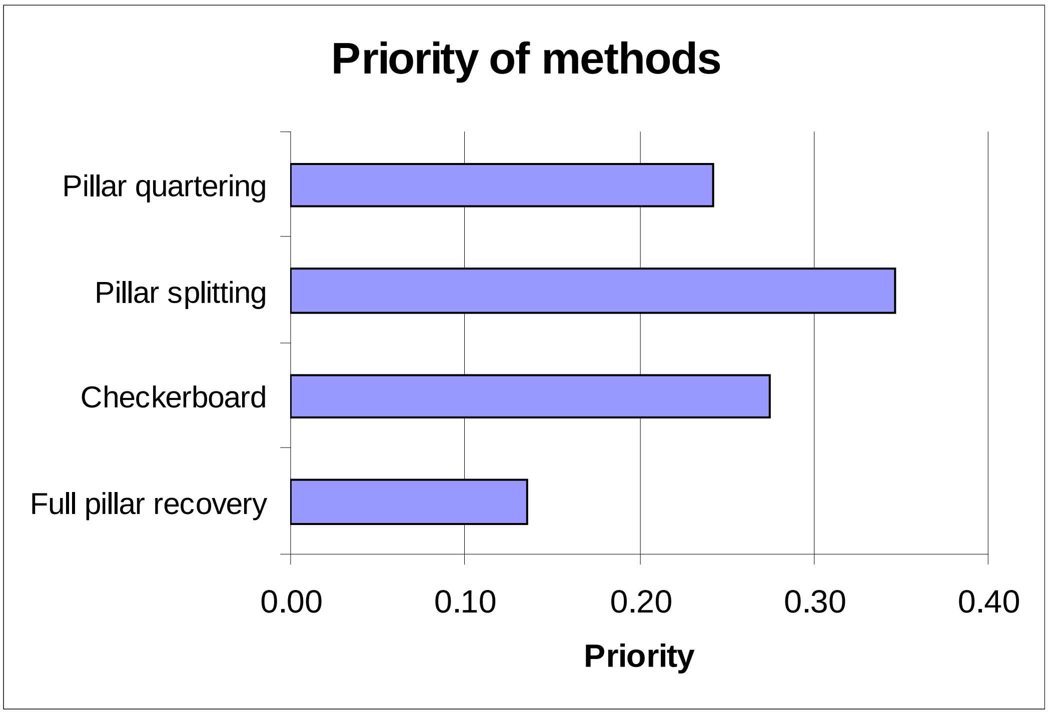


Figure 0–6 Final priorities of mining methods for hypothetical Panel A

The four mining methods were then compared, two at a time, for each of the sub-criteria and the final priorities shown in Figure 0–6 were obtained. The results show that pillar splitting has the highest priority, followed almost equally by pillar quartering and the checker-board method.

The priorities of the methods for the second panel, Panel B, were also determined. For this hypothetical case, the difference between the two panels was assumed to be as follows:

- a stream runs over the panel and the subsidence limit is reduced to 0.5m and groundwater disturbance is a major problem, the environmental issues are therefore very important.

The priorities of the main criteria were re-calculated for Panel B, resulting in the relative priorities shown in Figure 0–7, which shows how the priority of environmental issues has increased. The change in priorities of the main criteria resulted in the method priorities shown in Figure 0–9.

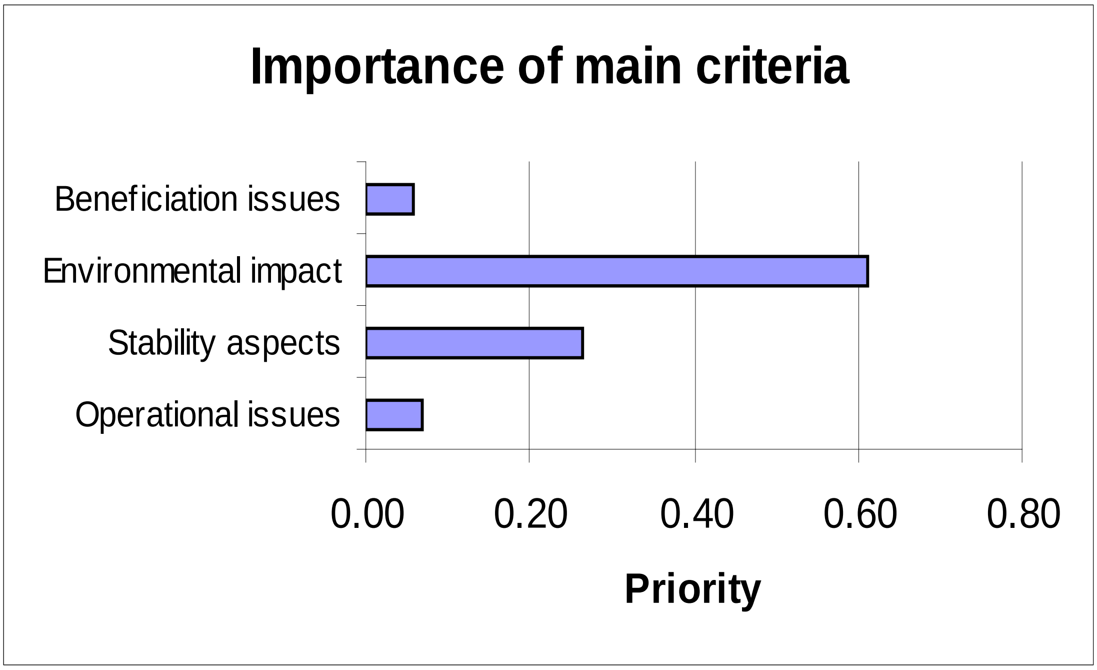


Figure 0–7   Relative importance of criteria for hypothetical Panel B

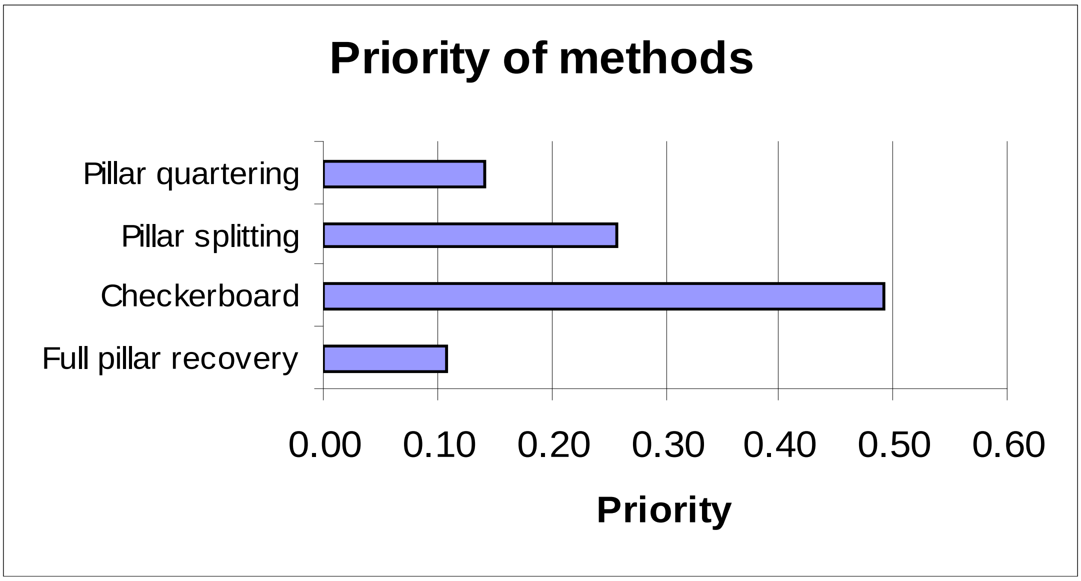


Figure 0–8   Priorities of mining methods for hypothetical Panel B

The results show that the checker-board method now becomes the most favourable method, mainly because it will result in the least surface subsidence. Note that the new priorities were obtained without re-evaluating all the methods and sub-criteria, only the relative priorities of the main criteria were changed.

This example shows the power of the AHP process. Greater sophistication is possible by incorporating feedback into the AHP spreadsheet, in which the importance of a criterion is related to the methods being considered etc. The spreadsheet makes use of only the basic capabilities of the method. Commercial software is available that allows very sophisticated systems to be evaluated. however, it is not considered warranted to overly complicate the decision process. The AHP method as used in the spreadsheet forces the decision maker to consider all factors that influence the selection of a mining method, and assists in prioritizing the options. It should confirm the “gut feel” of an experienced person. In addition, the method allows the decision maker to modify any of the relative weightings to suit the problem at hand.

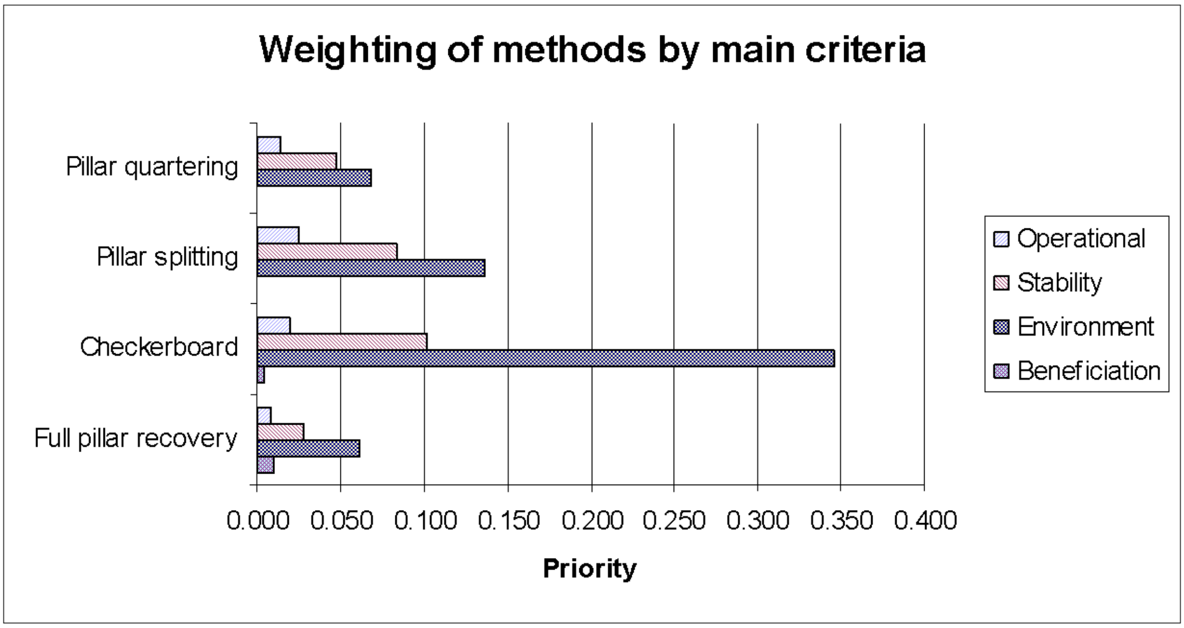


Figure 0–9 Weighting of methods by main criteria

Conclusions and recommendations

Investigations into the importance of secondary extraction indicated that for the period 1970 to 1997, 1.68 billion tons of coal lock in more than 1.7 million coal pillars was left underground. This covers an area of 27 x 27 km (729 km^2). This means that sufficient coal is left in the pillars to sustain ROM production for 17 years, excluding barrier pillars.

However, given the current assumptions, its appears that the application of pillar extraction is significantly smaller than what was previously believed. This is however caused by the specific assumptions used in this project. Improvement in the percentage extraction with adjustments made to the Nevid method for shallower depths will dramatically improve the situation. Extracting the barrier pillar between adjacent panels together with the adjacent pillars left to create the bleeder road will also make a significant difference as is the case at some existing operations. Carrying the water treatment cost well beyond the life of the mine will worsen the situation. With this in mind, and the fact that we are utilizing a diminishing resource which should be exploited to its full, tremendous effort should be put into water management to improve water quality. This should be backed by an even more dedicated research effort in finding more economic water treatment technologies, both from a capital and operating cost point of view.

Considering ashfilling, it should be realized that given the requirement of strength and stabilizing properties, it is highly unlikely that suitable ash mixtures can be developed within the cost framework.

Detailed literature review highlighted that various pillar extraction methods are applied successfully on a worldwide front. These methods include both methods for the secondary extraction of previously mined pillars as well as “pillars” designed and developed for immediate extraction such as the typical rib pillar methods.

It is critical to take note of the various constraints affecting successful pillar extraction both during the design phase as well as in the evaluation of previously mined pillars. Although it is well known that due to the dynamic nature of pillar extraction, and awareness of danger involved in pillar extraction, limited study into the investigation of falls of ground fatalities in South Africa indicated that pillar extraction is the least safe mining practice (Vervoort [1990], Canbulat and Jack [1998]).

Although the database was small and consequently the correlation low, the following conclusions were nevertheless drawn from the site visits:

a) The initial safety factor of the pillars has a major effect on the pillar conditions during pillar extraction, specifically near the stooping line.
b) The pillar conditions at the stooping line tend to deteriorate more rapidly as the age of the pillars being extracted increases.
c) Mine personnel working with pillar-extraction panels do not perceive the age of the workings as contributing to the hazard of pillar extraction.
d) About 40 per cent of the tonnage mined at the time had been produced from panels older than three years or with a safety factor of less than 2.0.

Site visits highlighted that except for the Tshikondeni Colliery and the Sasol mines, all the mines were mining previously developed sections whose panels were not originally designed for total extraction mining methods.

It was also apparent that the mining method employed, and especially the pillar mining sequence, was site-specific. As such, the design and the mining methods used were specifically adapted to suit local mining and geological conditions.

In all the feedback received it was claimed that this method of mining was as safe as or even safer than normal bord-and-pillar development.

It was further evident that extraction efficiency (of single pillars) is site and operator-specific. The final extraction efficiency is normally a matter of judgement on the part of the operator.

There was no difference in coal quality except in panels where high levels of oxidation were reported.

It was reported by the mines that the cost of later pillar extraction is generally lower than the development cost when pillar extraction follows directly after pillar development. This lower cost is most probably the result of lower support requirements during secondary extraction. However, where extensive clean–up of old panels has to be done along with the provision of extensive additional roof support and the installation of support services, the cost of pillar extraction increases.

It is concluded that a qualitative and quantitative approach to site inspections prior to the opening of an old mined-out bord-and-pillar section is critical. It was generally felt that detailed decision-making about the method to be employed was only possible after a thorough in-section evaluation of the reserves available and the prevailing mining and panel conditions had been done.

Review of current pillar extraction practices showed that pillar extraction takes many forms and mines have adopted methods of removing individual pillars to suit their particular needs. In ‘traditional’ stooping, it was recommended practice to remove or destroy all snooks in order to allow the goaf to cave thereby relieving the stress on the caving pillar line. Many of the pillar extraction methods now used deliberately leave pre-designed snooks that prevent immediate caving but will crush over time.

One major disadvantage of keeping up the goaf by the use of pre-designed snooks or by the use of checker-board mining is the uncertainty of when the snooks or remaining pillars are going to crush and allow the overburden strata to settle.

Contrary to previously held views, mines now do not believe that pillar extraction is a less safe method than pillar development. This may be because pillar extraction is now done by continuous miner, often by means of remote control, and also that the incorporation of section employees in more risk assessment procedures has introduced a greater awareness amongst the underground operators of the inherent dangers in pillar extraction. Also, more use is now made of ‘partial’ pillar recovery and checker-board systems where the formation of a goaf edge is prevented, thereby removing a hazardous area from the system.

The cost of pillar extraction in comparison to pillar development is reported to be higher by some mines but lower by others. Much depends on a mine’s costing procedures and whether pillar extraction follows directly after pillar development or whether old panels have to be rehabilitated.

Pillar extraction by means of shortwall equipment has been done successfully but a particular problem can be the rate of retreat through the pillars. Careful consideration must be given to the logistics of utilising what is considered to be a highly capital intensive method for the recovery of pillars.

The recovery of old pillars by underground pillar extraction was shown to be feasible in the No 4 Seam and the No 2 Seam in the Witbank Coalfield. Experience is being gained which should be beneficial to the industry in the wider application of pillar extraction to other parts of the Coalfield where suitable reserves may be found.

This study highlighted that the so-called Nevid Method has a potential for future pillar extraction in South Africa. However, currently, it cannot be applied at shallower depths because of pillar dimensions required. It is therefore a study was conducted to determine the extraction dimensions, lift widths and safety factors for NEVID pillars at various depths. The results are presented below.

Depth	ctr	ctl	cb	lw	A	Q	SF
160	6.0	2.0	5.0	7.2	140.9	96.7	0.35
140	5.0	3.0	5.0	6.0	107.5	84.6	0.37
120	4.0	2.0	4.0	5.0	78.7	77.1	0.36
100	3.0	2.5	3.0	4.5	53.0	59.1	0.35
80	2.4	2.4	2.5	3.6	36.0	47.5	0.35

The importance of panel width was also shown with this study. Leaving artificial barrier pillars was recommended if the safety factors of the pillars being extracted small and the panel is too wide.

It is recommended that a decision making process for pillar extraction should follow a flow sheet analysis. In general, five important evaluations were found to be considered. These are:

- Rock engineering evaluation
- Environmental risk evaluation
- Mining evaluation
- Coal beneficiation, and
- Financial evaluation

All these factors have their own constraints and limitations. It is therefore decided to develop flow sheets for the above given evaluations.

This study also indicated that selection of the mining method is very important. It is therefore a mining method selection methodology was developed. The following methods of coal pillar recovery were considered.

- Full pillar recovery in which all the pillars are recovered using typical pillar extraction methods;
- Checker-board pillar recovery: in which every second pillar is recovered;
- Pillar splitting: every pillar is split into two smaller pillars by driving a roadway through the pillar;
- Pillar quartering: every pillar is split into four smaller pillars by driving two roadways at right angles through the pillar.

In order to select the best method, the differences between the methods were first listed, under the topics of rock engineering, mining, environmental and beneficiation. Similarities between the methods were ignored, since they would apply equally to all the methods, and would not play a role in selecting a particular method above another.

Once the differences were identified, the requirements for success of the methods were listed, based on the differences. These lists formed the basis for drawing up a checklist that may be used to assess the applicability of each mining method to a particular panel. This process allows unsuitable methods to be eliminated. If more than one mining method survives the checking process, a decision support system may be used to select the best method. The decision support system is based on the Analytical Hierarchy Process developed by Saaty (1994). A spreadsheet has been developed which uses the list of differences between the methods to evaluate their suitability for a given situation.

Finally, it is strongly recommended that the methods and guidelines given in this project should be applied in an actual pillar extraction project in order to determine the applicability of them.

References

Anonymous (1990) Thin-seam mining, *Colliery Guardian*, February, pp 45-47.

Anonymous (1999) Statistical summary of accidents reported to the Chief Inspector of Mines for the period 1 January 1984 to 31 December 1998, *Department of Minerals and Energy*, Pretoria.

Basu, K. (1999) My research, http://fbox.vt.edu:10021/K/kbasu/research.html, 6 October.

Baxter, R., (1998). Coal production in South Africa - an overview 1997. Coal International May 1998. pp 106 -100.

Beukes, JS.(1989) Stooping practices in South African collieries, Part 1: Rib pillar extraction, *Chamber of Mines of South Africa, Report No. 3/89*.

Blaiklock, J (1992) A Kentuckian vote for continuous mining, *Mining Magazine*, June, pp 365-366.

Bryan, A, Bryan, JG and Fouche, J (1964) Some problems of strata control and support in pillar workings, *The Mining Engineer*, London, Vol. 123, pp. 238-254.

Canbulat, I. and Jack, B.W. (1998) *Review of current design methodologies to improve the safety of roof support systems, particularly in the face area, in collieries.* SIMRAC Final Project Report, COL 328, December.

Canbulat, I and Johnson, R. (2002) Anglo coal pillar extraction project: pre-feasibility modelling. Confidential Consultancy Report. March. Report No: JP-011-01-2002

Chase, FE, McComas, A, Mark, C and Goble, CD (1997) Retreat mining with mobile roof supports, *Proceedings: New Technology for Ground Control in Retreat Mining*, http://www/cdc.gov/niosh/97-133.html, 8 January.

Clark, J and Caldon, JH (1982) Thin seam coal mining technology, *Noyes Data Corporation*, New Jersey, USA.

De Beer, JJS, Hunter, F and Neethling, AF (1991) Rib-pillar mining at Sigma Colliery, *Journal of the South African Institute of Mining and Metallurgy*, Vol. 91, No. 6, June, pp 209-218.

Falconer, KW (1989) *A review and cost comparison of the three main methods of underground coal mining in South Africa*, MSc Thesis, University of the Witwatersrand, Johannesburg.

Galvin, JM, Hebblewhite, BK and Salamon, MDG (1997) Australian coal pillar performance, *Australian Mining*, pp 33-38.

Gericke, P (1989) The evolution of total extraction technology as applied by Middelbult Colliery, *SAIMM School: The Total Utilisation of Coal Resources*, Vol. 1, Witbank.

Hardman, D.R., (1989). The consequences of leaving vast mined-out areas standing on pillars. *In:* Total Utilization of Coal Resources, SAIMM School, Witbank.

Heasley, KA (1997) A new laminated overburden model for coalmine design, *Proceedings: New Technology for Ground Control in Retreat Mining*, http://www/cdc.gov/niosh/97-133.html, 8 January.

Jefrey, L.S., (2000). Literature review – Current status of resources and reserves in the Northern Witbank-Highveld coalfield, subtask 2 draft report, Coaltech 2020.

Landman, GVR (1987) *Thin seam extraction at the Durban Navigation Collieries*, MSc Thesis, University of the Witwatersrand, Johannesburg.

Langdon, B (1998) Coal mine support: Conceptual leaps or pragmatic steps? *Journal of the Institute of Mining and Metallurgy*, December, pp 325-330.

Lind, GH (1999) *The development of a costing framework to compare two types of underground mining methods in a typical South African coal mine for use in decision making*, MSc Thesis (Project Report), University of the Witwatersrand, Johannesburg.

Livingstone-Blevins, G and Watson, S (Eds) (1982) Pillar extraction, *Chamber of Mines of South Africa, Report No. NS 469*, Johannesburg.

Madden, BJ (1987) The effect of mining method on coal pillar strength, *Chamber of Mines of South Africa, Research Report 15/87*, Johannesburg.

Madden, BJ (1988) ‘Squat’ pillar design, *Coal International*, Vol. 7, No. 1, January, pp 6-9.

Madden, BJ (1989(a)) Squat pillar design in South African collieries, *SANGORM Symposium: Advances in Rock Mechanics in Underground Coal Mining*, September, pp 83-90.

Madden, BJ (1989(b)) Reassessment of coal pillar design, *SAIMM School: The Total Utilisation of Coal Resources*, Vol. 1, Witbank.

Madden, BJ (1990) The ‘Squat” pillar design formula and some advantages of its application, *South African Colliery Managers’ Association (SACMA), Papers presented 1984 - 1988*, Chamber of Mines of South Africa, pp 205-229.

Madden, B.J., Canbulat, I., Jack, B.W. and Prohaska, G.D., (1995). A reassessment of coal pillar design procedures, SIMRAC Final Project Report – COL021, CSIR-Division of Mining Technology, December.

Madden, BJ and Canbulat, I (1996) Reassessment of coal pillar design procedures, CSIR *Miningtek Report No. NS 1479*, Johannesburg.

Madden, BJ (1997) Current and future risks and casual issues relating to rock engineering on South African coal mines, *Final Project Report No. SIMRISK 401*, SIMRAC, Johannesburg.

Mark, C and Chase, FE (1999) Analysis of retreat mining pillar stability (ARMPS), *Proceedings: New Technology for Ground Control in Retreat Mining*, http://www/cdc.gov/niosh/97-133.html, 8 January.

Mark, C, Chase, FE and Zipf, RK (1999) Preventing massive pillar collapses in coal mines, *Proceedings: New Technology for Ground Control in Retreat Mining*, http://www/cdc.gov/niosh/97-133.html, 8 January.

Mark, C, McCall, FE and Pappas, DM (1999) A statistical overview of retreat mining of coal pillars in the United States, *Proceedings: New Technology for Ground Control in Retreat Mining*, http://www/cdc.gov/niosh/97-133.html, 8 January.

Marx (1996) *An Activity Based Costing Approach to Fall of Mine Accidents in a South African Gold Mine*, Project Report, Potchefstroom University, Potchefstroom.

McCosh et al (1989) Stooping with roofbolt breakerlines on the Alfred seam, SACMA papers 1984-1988, pp 389-404.

Minerals Bureau, **(1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997)**. Operating and developing coal mines in the Republic of South Africa.

Oberholzer, J.W., et al., 1997. Determine the need to research the time related stability decay of bord and pillar systems, SIMRAC Final Project Report – COL 439, CSIR-Division of Mining Technology.

Plaistowe, RHA, Poultney, MO, van Schalkwyk, B, Hichens, RL and Bradbury, TJ (1989) Decision-making considerations for pillar extraction, *SAIMM School: The Total Utilisation of Coal Reserves*, Vol. 1, Witbank.

Rogers, PR (1989) Rib pillar extraction at New Denmark Colliery, *SAIMM School: The Total Utilisation of Coal Resources*, Vol. 1, Witbank.

Ryder, J.A. (1992) Determination of the quatity of ashfill required to stabilize and prevent undue subsidence of old workings. CSIR Internal Report. Report No: B03/92. October 1992.

Salamon, MDG (1967) A method of designing bord and pillar workings, *Journal of the South African Institute of Mining and Metallurgy*, Vol. 68, pp. 55-67.

Salamon, MDG and Munro, AH (1967) A study of the strength of coal pillars, *Journal of the South African Institute of Mining and Metallurgy*, Vol. 68, pp. 68-78.

Salamon, MDG and Oravecz, KI (1973) Rock mechanics in coal mines, *Chamber of Mines of South Africa Research Organisation, Project Report No. CM/807/66*.

Salamon, MDG and Wagner, H (1985) Practical experiences in the design of coal pillars, *Miningtek Report NS 584*.

Schumann, EHR (1982) Controlled subsidence of the Blackhill-Greenside railway line: Part 1, *Chamber of Mines Research Organisation, Research Report No. 8/83,* Johannesburg.

Steart (1954) Strength and stability of pillars in coal mines, Journal of the Chemical, Metallurgical and Mining Society of South Africa, March, pp. 309-325.

Strata Engineering (Australia, 2002). Initial Assessmnet of the Geotechnical Constraints to Undertaking Pillar Extraction Operations in Existing Bord and Pillar Workings Containing "Small" Pillars. *Confidential Consultancy Report to Anglo Coal*. Report No: 01-183-AAC/1. January.

Skybey, G (1982) Geotechnical evaluation of Wongawilli extraction system at Coalcliff Colliery, *Australian Coal Industry Research Laboratories Ltd, Published Report 82-11*.

Vervoort, A (1990a) Falls of ground in South African collieries during the period 1970-1988, Part I: Review of fall of ground fatalities and injuries, *Reference Report No. 5/90, COMRO*, Johannesburg.

Vervoort, A (1990b) Falls of ground in South African collieries during the period 1970-1988, Part II: Description of fatal falls of ground, *Reference Report No. 6/90*, COMRO, Johannesburg.

Vervoort, A (1990c) Falls of ground in South African collieries during the period 1970-1988, Part III: Effect of exploitation method, *Reference Report No. 7/90, COMRO*, Johannesburg.

Vervoort, A & Prohaska, G (1991) Dynamic roof movement in intersections during pillar extraction, *Mining Science and Technology*, vol. 13, Amsterdam, pp. 351-357.

Wagner, H (1981) An investigation of pillar extraction systems to improve percentage extraction in South African collieries, *Coal Symposium*, Pretoria, 11 May.

Wagner, H and Madden, BJ (1984) 15 Years Experience with the design of coal pillars in shallow South African Collieries, ISRM Symposium, Cambridge, U.K., 3-6 Sep ’84, pp 391-399

Walker (1995) Behind the miner, World Mining Equipment, vol. 19, No. 4, May 1995, pp6-8, 10-11.

Willis, RPH and Hardman, DR (1997) Projections of likely changes in mining circumstances, conditions and technologies which may affect safety and health risks, *Final Project Report No. SIMRISK 401, SIMRAC*, Johannesburg.

York,G et al. (1998) Develop guidelines for the design of pillar systems for shallow and intermediate depth, tabular, hard rock mines and provide a methodology for assessing hangingwall stability and support requirements for the panels between pillars. SIMRAC report GAP 334. CSIR, Division of Mining Technology.

Appendix 1: Comparison of Geometry and Resources

												Approx. Output	
Colliery	Seam	Depth (m)	Thickness (m)	Extraction Height (m)	Pillar Width (m)	Bord Width (m)	S.F.	Age of Panels	Panel Width (m)	Equipment	Section Labour	Ton Per Shift	Ton Per Month
Greenside	No. 5	30 - 60	1.8	1.8	8.5	7.5	1.8	+/- 13	170 to 200	Joy 12CM6 + 8t S/cars	18	860	19000
New Clydesdale	No. 2	50 - 70	+/- 4	3.6	8.5	7.5	1.8	+/- 20	170 to 200	Joy HM9+ 8t S/cars	14	950	38000
Gloria X	No. 2	150	5	4.5 - 5.0	21	7	1.8	7	175	Joy HM17+ 18t S/cars	12	1200	50000
Blinkpan X	No. 2	80	4.2	4.2	12.2	6.8	1.7	+/-3.5	121	Joy HM9+ 10t S/cars	16	911	44500
Arthur Taylor	No. 4	63	4.2	3.2	10.5	6.5-7.5	2	4	210	Joy HM31+ 16t haulers	19	1125	49600
Boschman's	No. 4	60	+/- 5	3.8	10.5	6.5	1.8	2	160	Joy HM31+ 10t S/cars	15	1136	50000
Twistdraai	No. 4	160	3.5	3.5	18	6.5 - 7	1.8	+/- 1	150	Joy HM31+ 16t Sascars	11		44000
New Denmark #	No. 4	200	1.8	1.8	18	7	2	4	75	Shearer	-	848	44433
DNC	U & L	250	3.1 - 3.8	3.1 - 3.8	25	4.5 - 5	1.7/2.1	+/- 5	215	VA AM75+ 10t S/cars	15	750	30000
ZAC 1 X	M	232	1.45	1.45	10.4	6.6	1.8	0.5 - 3	74	Joy + 4t TT units	13	434	17653
ZAC 2 X	M	110	2.3	2.3	13.6	6.4	2.36	0.5 - 3	86	AM 75 + 8t Wagners	15	520	23019
X Checker-board			# Shortwall pillar extraction										

Appendix 2: Geology and support efficiency

		G/side	**NCC**	**Gloria**	**B/pan**	**ATC**	**B/mans**	**T/draai**	**N. Denmark**	**DNC**	**ZAC 1**	**ZAC 2**
Sill thickness (m)		N/A	N/a	N/A	9 to 18	N/A	N/A	8	N/A	90	5.7	1.7 & 3.9
Distance to sill				N/A	50	N/A	N/A	30	N/A	95	13	13 & 16
Immediate roof? And thickness				coal/shale	coal, 0.5	coal,1.2m	coal,+/-1m	sh/sst,.4/.6m	sandstone	shale	9m sst	7.1m sst
Immediate floor? And thickness				sandstone	sandstone	shaley/sst	18m sst	mic sh,mudst	sandstone	shale	0.8m sst & sh	0.6m sh
Roof and support conditions												
Roof competence		Fair/good		varies	good	good	good in roads	good	good		good	excellent
Roof fall: density and height?				shale & slips	none	none	none	sporadic	sporadic	upto 5m,5/pa	none	none
Support type		Resin r/b		1.5m mech, 1.5m M16 resin,2m M20 resin	roofbolts	resin roofbolts	resin roofbolts	full col resin, 20mm rebar	roofbolt	mech,resin & cable anchor	no syst. support	no syst. support
Support efficiency		good		-	good	good	good	-	good	inefficient	good	good
Support pattern		3/row,2m between rows		2 bolts/row 5m apart, 2m row spacing	2 bolts/row, 2.5m spacing	1.2mspacing	2 bolts every 1m	4 bolts every 3m	2m x 2m	1.5 m in all directions	depends on conditions	no syst. support
Installation of support		Roofbolter		Roofbolter	Roofbolter	Roofbolter	roofbolter	roofbolter	wombat	Roofbolter	roofbolter	roofbolter
Type of support failure?		none		Mech slip	none	none	none	none	sporadic	Frittering	none	none
Support length(m)		1.5		2m resin at slips, 6m cables	1.5m & 1.9m	1.2 m	1.2m	1.2 m	1.5 m	1.8m bolts 5m anchors	0.5 & 0.9 m	varies
Current support conditions		N/A		moderate	good	good	good	good	N/A		good	good
Additional information												

Discontinuities in the roof and pillars		none	minor	at +/- 200m	none	none	some faulting	minor	none	none	yes	yes
Pillar punching		none	none	none	none	none	none	none	limited	none	some areas	some areas
Any weakness in pillar		none	none	slips in pillars	none	yes	none	none	none	shale parting	none	none
Roof pillar contact		good	coal roof	coal	coal	good	coal	-	good	-	good	good
Pillar fracturing		very little	little	at slips/dykes	minimal	at delayed goafing	minimal	none	minor scaling	yes	yes	yes
Top/bottom coaling		none	none	none	none	none	none	none	none	none	none	none
Presence of slips And/or faults		very few	plenty	yes	stringers /slips	none	occasional	sporadic	none	none	yes	yes
Presence of stone Or shale layers		None	sst band + floating stone	some areas	shale in roof	.3-.4m shale layer	shaley sst band 3m from floor	floating st.	none	Yes	yes	yes

Appendix 3: Miscellaneous

	G/side	**NCC**	**Gloria**	**B/pan**	**ATC**	**B/mans**	**T/draai**	**N. Denmark**	**DNC**	**ZAC 1**	**ZAC 2**
Problems	Cleaning & Re-support Old areas	Clean,support, make safe & ventil.	Mining pillars which have slips	none	none	none	Scaling & slabbing in high Seams	Panels limited to 75 m in width	Excessive sidewall failure	None	none
Solutions			mine 90^{o} to sli^{p}	N/A	N/A	N/A	?	-	s/w support	N/A	N/A
Change in coal quality?	none	not known	none	none	none	none	less dirt	more dirt	none	None	none
Change in coal size?	bigger	bigger	+/- 5% larger	none	none	bigger	none	none	none	Bigger	bigger
Surface disturbance	yes	yes	none	none	yes	yes	yes	yes	none	None	yes
Subsidence extent	-	-	N/A	N/A	-	whole panel	limited	little	none	N/A	Minimal
Subsidence magnitude	50% of h	+/-1.2m	N/A	N/A	1.5m	1m to 3m	?	0.8 m	none	N/A	Minimal
Water table effect	yes	yes	N/A	none	none	yes	yes	yes	none	Yes	Yes
Spon. com problems?	none	none	none	none	none	none	none	none	yes	None	None
Methane problems	minor	minor	none	none	none	none	yes	yes	yes	None	None
Airflow problems	none	none	none	none	none	yes	yes	yes	none	None	None
Problems with geotech/geol.	none	none	none	none	none	none	none	none	none	None	None
Pillar/panel behaviour?	-	-	-	-	-	-	-	-	-	Stable	Stable
Support problems?	black shale	-	at slips	-	none	none	none	sporadic	yes	none	None
Sidewall spalling?	minor	at +/- 70 m	at slips	-	slight	slight	none	yes	yes	none	None
Pillar behaviour?		stable	stable	-	stable	some crush	none	stable	crushing	stable	Stable
Influence on adjacent Panels	yes	none	none	none	none	none	none	none	increased loading	none	None
Financial											
Op. Cost of PE?	cheaper	cheaper	Material cost=.5 devt.cost	+/- R3/t	-	R16.53/t	R13.95	R9.47/t in 1991	1/3 of devt.	R1.5 to R2.5 R/t cheaper	R1.5 to R2.5 R/t cheaper
Op cost of devt.panels?	-	-	R1.80/t mining	+/-R3.7/t	-	R11.52/t	R20.0	R6.6 /t	-	-	-

Cause of difference	lower pick & support costs	lower pick costs	training, risk assesst. Vent. Contr.	absence of dykes and poor ground	-	re-support & re-equip old panels	lower support & pick costs	lower tons & higher support costs	Lower suppor costs	easier cutting	Easier Cutting
Effect on revenue?	none	none	resource recovery	none	none	?	none	none	none	yes, larger coal	Yes, larger Coal
Engineering											
Equipment availability?	better	better	same	same	same	same	same	same	Lower	same	same
Equipment modifications?	yes	yes	yes	none	yes	yes	yes	none	yes	no	no
Cost of equipment damage?	none available	-	+/- R1000 for sprays	none	-	-	minor	N/A	R150000 / buried m/c	none	none
Safety & health											
Effect on safety?	better	better	none	none	none	none	none	none	none	none	none
Mine standards for PE?	yes	yes	yes	no	yes	yes	yes	N/A	yes	yes	yes

Appendix 4: Example of checklist data collection form

Checklist to evaluate previous and present pillar extraction operations

Pillar extraction is undertaken in order to increase the coal recovered from a given in-situ resource. It may be done to extend the life of a mine, in order to continue supplying customers with a particular quality of coal or it may be done to maintain production at a particular level when existing development panels have encountered poor mining conditions and there is a sudden shortage of ‘pit room’. Whatever the reason for adopting pillar extraction, it must be done safely and profitably with a minimum amount of disturbance to the environment.

As part of the Coaltech project an evaluation of the current practices was required. To help facilitate the above the following checklist was developed.

1. General information

Colliery	
Mine group	
Location	
Seams mined	
Coalfield	

2. Extraction method

Please indicate what the mining method is and/or what has been used at the mine.

Pillar extraction methods:	
Conventional pillar extraction	
Mechanised pillar extraction	
Wall mining methods:	
Shortwall	
Longwall	
Partial extraction:	
Checker-board	
Split and Quarter	
Other methods	
Backfill assisted mining	
Auger mining	
Other methods?	

3. Extraction sequence

Please explain the extraction sequence utilised**. (Attach figures if available)**

4. Extraction equipment

Please indicate the equipment used to mine the coal in a typical section or mining unit.

Equipment	**Type**	**Capacity**	**Number**
Continuous miner			
Roadheaders			
Shortwall			
Longwall			
Conventional equipment			
Shuttlecars			
Continuous haulages			
Other:			

5.1 Production rates

Output	/ Shift	/ Month	Av. (3 months)
Development panels			
Pillar extraction panels			
Other			

5.2 Personnel employed

Number of employees	**Number**	**Can you supply a detailed breakdown**	
		Yes	**No**
Development panels			
Pillar extraction panels			
Other			

6. Original design parameters

Pillar size extracted:		
Width		
Height		
Bord width		
Seam thickness		
Depth to floor		
Parting distance to higher Seams		
Parting distance to lower Seams		
Thickness of adjacent Seams		
Were adjacent Seams previously mined, if so, what pillar sizes, bord widths and pillar heights were used?	**Yes**	**No**
Were pillars superimposed		
Pillar designed safety factor per section		
Are barrier pillars used?		
If so, what are their widths?		

7. Current pillar conditions and measurements

Current dimensions	**(m)**
Pillar width	
Bord width	
Total spalling (from the marks in the roof)	
Mining height	
Stone dusting	
Time since dusting	
If CM section, cutting marks on the sidewalls	
Sill thickness	
Distance to sill	
Immediate roof? And thickness	
Immediate floor? And thickness	
Number of roads to calculate panel width	

7.1 Roof and support conditions

Roof competence	
If there is any roof fall: density and height?	
Support type	
Support efficiency	
Support pattern	
Installation of support	
If there is failure in support, type of failure?	
Support length	
Current support conditions	

7.2 Additional information

Discontinuities in the roof and pillars	
Pillar punching	
Any weakness in pillar (soft layers)	
Roof pillar contact	
Pillar fracturing	
Top/bottom coaling	
Presence of slips and/or faults	
Presence of stone or shale layers	

7.3 Problems experienced with pillar extraction + solutions if possible

8. Age of pillars

Average age of pillar (per section)	
Age of panel being extracted	

9. Quality

		YES	NO
9.1	Were there noticeable changes to coal quality from pillar extraction panels compared to development sections? If yes, what were the changes?		
	What were the variations in yield?		
9.2	Were there noticeable changes to coal size grading from pillar extraction panels compared to development sections? If yes, what was the change in coal grading size?		
	Did this effect revenue?		

10 Surface

	YES	NO
Was surface disturbance caused by pillar extraction panels?		
If yes: Extent of subsidence		
If yes: Magnitude of subsidence		
Did pillar extraction affect the water table?		
Did pillar extraction affect upper or lower Seam mining, if there is one?		

11. Underground

	YES	NO
Did pillar extraction result in any problems with spontaneous combustion?		
If yes, can you provide records or evidence?		
Did pillar extraction result in any problems with methane accumulations in or around the goaf line?		
If yes, can you provide records or evidence?		
Did pillar extraction result in any problems with airflow?		
If yes, can you provide records or evidence?		
Did pillar extraction result in any problems with geotechnology or geology		
If yes, can you provide records or evidence?		
Pillar/Panel behaviour		
Roof – support, secondary support, collapses		
Sidewalls – spalling, prior/during extraction – extent of		
Pillar behaviour during extraction: Eg. Stable, crushing, failing		
Did pillar extraction affect adjacent panels?		
If yes, please specify the effects.		

12. Costs/Revenue

What was or is the operating cost of pillar extraction
What was or is the operating cost for development panels?
What aspects of the operations resulted in the major differences?
Was revenue influenced by pillar extraction operations? If so, what was the influencing factor?

13. Engineering

Did pillar extraction operations result in changes to equipment availability? If so, to what extent?
Were equipment modifications necessary? If so, please briefly indicate modifications
Can you provide detail of cases of damage / collapses on equipment and costs thereof

14. Safety and Health

To what extent did pillar extraction operations influence the safety record of the mine?		
Can you provide safety records as support evidence?	**YES**	**NO**

15. General

	YES	NO
Do mine standards for pillar extractions exist		
Can section plans of areas visited or where pillar extraction has been done be made available?		
Can documentation pertaining to pillar extraction, e.g. productivity and technical reports, where collapses have occurred be made available?		

Appendix 5: Tables A1 to A7

Table A51: Assignment of probabilities for local stability

LOCAL STABILITY								
PILLAR INSTABILITY			**ROOF INSTABILITY**			**FLOOR INSTABILITY**		
Pillar age		Probability	Age of workings	Risk level	Probability	Age of workings		Probability
Less than 3 years	Extremely low	1.00E-06	Less than 3 years	Extremely low	1.00E-06	Less than 3 years	Extremely low	1.00E-06
3 to 10 years	Low	1.00E-04	3 to 10 years	Very low	1.00E-05	3 to 10 years	Very low	1.00E-05
10 to 20 years	Moderate	1.00E-03	10 to 20 years	Low	1.00E-04	10 to 20 years	Low	1.00E-04
More than 20 years	High	1.00E-02	More than 20 years	Moderate	1.00E-03	More than 20 years	Moderate	1.00E-03
Pillar scaling			**Roof conditions**			**Floor composition**		
None	Extremely low	1.00E-06	V Good	Extremely low	1.00E-06	Sandstone > 1m	Extremely low	1.00E-06
Minor	Low	1.00E-04	Minor failures	Low	1.00E-04	Laminated SST&Shale	Very low	1.00E-05
Moderate	Moderate	1.00E-03	Some collapsed	Moderate	1.00E-03	Shale/mudstone	Low	1.00E-04
Severe	Very high	1.00E-01	Severe collapses	Very high	1.00E-01			
Pillar discontinuities			**1.48.1.1.1 Discontinuities in roof**			**Presence of water**		
None	Extremely low	1.00E-06	None	Extremely low	1.00E-06	None	Extremely low	1.00E-06
Minor cleats	Low	1.00E-04	Minor joints	Low	1.00E-04	Damp	Low	1.00E-04
Cleats and joints	Moderate	1.00E-03	Slips and joints	Moderate	1.00E-03	Wet	Moderate	1.00E-03
Frequent major slips	High	1.00E-02	Frequent major slips	High	1.00E-02	Flooded	High	1.00E-02
Factor of safety			**Roof composition**			**Floor undulations**		
Greater than 2.0	Extremely low	1.00E-06	Sandstone > 1m	Extremely low	1.00E-06	None	Extremely low	1.00E-06
1.6 to 2.0	Low	1.00E-04	Laminated SST&Shale	Low	1.00E-04	Minor	Very low	1.00E-05
1.3 to 1.6	High	1.00E-02	Shale/mudstone	Moderate	1.00E-03	Occasional rolls	Low	1.00E-04
Less than 1.3	Very high	1.00E-01	Friable/Claystone	High	1.00E-02	Major rolls	Moderate	1.00E-03

Table A2: Assignment of probabilities for multi seam stability – pillar failure and parting stability

MULTI-SEAM PILLAR FAILURE			**PARTING INSTABILITY**		
Other Seam age	**Probability**	**Probability**	**Parting thickness**	**Probability**	**Probability**
Less than 3 years	Extremely low	1.00E-06	> Pillar centres	Extremely low	1.00E-06
3 to 10 years	Very low	1.00E-05	> Bord width	Low	1.00E-04
10 to 20 years	Low	1.00E-04	< Bord width	High	1.00E-02
More than 20 years	Moderate	1.00E-03	< 2m	Very high	1.00E-01
Factor of safety other seam			**Parting composition**		
Greater than 2.0	Extremely low	1.00E-06	Sandstone	Extremely low	1.00E-06
1.6 to 2.0	Low	1.00E-04	Laminated SST&Shale	Very low	1.00E-05
1.3 to 1.6	Moderate	1.00E-03	Shale/mudstone	Low	1.00E-04
Less than 1.3	High	1.00E-02	Friable/claystone	Moderate	1.00E-03
Superposition					
Not required	Extremely low	1.00E-06			
Pillars superimposed	Very low	1.00E-05			
Partial superposition	Low	1.00E-04			
No superposition	Moderate	1.00E-03			
Other seam barriers					
Wide barriers	Extremely low	1.00E-06			
Barriers = pillar width	Low	1.00E-04			
No barriers	Moderate	1.00E-03			

Table A3: Assignment of probabilities for multi seam stability – mining above/below previous goaf

MULTI-SEAM MINING BELOW GOAF			MULTI-SEAM MINING ABOVE GOAF		
Seam separation	**Probability**	**Probability**	**Seam separartion**	**Probability**	**Probability**
> Pillar centers	Extremely low	1.00E-06	> Pillar centres	Low	1.00E-04
> Bord width	Low	1.00E-04	> Bord width	Moderate	1.00E-03
< Bord width	Moderate	1.00E-03	< Bord width	High	1.00E-02
< 2m	High	1.00E-02	< 2m	Very high	0.1
Goaf consolidation			**Goaf consolidation**		
Goaf age > 5 years	Extremely low	1.00E-06	Goaf age > 5 years	Extremely low	1.00E-06
Goaf age 2 to 5 years	Low	1.00E-04	Goaf age 2 to 5 years	Low	1.00E-04
Goaf age < 2 years	Moderate	1.00E-03	Goaf age < 2 years	Moderate	1.00E-03
Remnant pillars			**Remnant pillars**		
None	Extremely low	1.00E-06	None	Extremely low	1.00E-06
Small snooks	Low	1.00E-04	Small snooks	Low	1.00E-04
Partial pillars	Moderate	1.00E-03	Partial pillars	Moderate	1.00E-03
Full pillars	High	1.00E-02	Full pillars	High	1.00E-02
Hydrological hazard					
Dry	Extremely low	1.00E-06			
Small inflow expected	Low	1.00E-04			
Water accumulations	Moderate	1.00E-03			
Flooded	High	1.00E-02			

Table A4: Assignment of probabilities for regional stability – caving and subsidence hazards

CAVING HAZARD			**SUBSIDENCE HAZARD**		
Dolerite sills	**Probability**	**Probability**	**Subsidence mode**	**Probability**	**Probability**
No dolerite	Extremely low	1.00E-06	No subsidence expected	Extremely low	1.00E-06
Dolerite < 20 m	Low	1.00E-04	Depth > 100 x height	Low	1.00E-04
Dolerite 20 - 40 m	Moderate	1.00E-03	Depth 10 to 100 x height	Moderate	1.00E-03
Dolerite > 40m	High	1.00E-02	Depth < 10x height	High	1.00E-02
Sandstone beams			**Surface usage**		
No sandstone	Extremely low	1.00E-06	Unimproved	Extremely low	1.00E-06
10 - 20m sandstone	Low	1.00E-04	Agriculture	Low	1.00E-04
20 - 40m sandstone	Moderate	1.00E-03	Infrastructure	Moderate	1.00E-03
			Dwellings	High	1.00E-02
Panel span/depth ratio			**Hydrology**		
Span > 3xdepth	Extremely low	1.00E-06	No groundwater	Extremely low	1.00E-06
Span 2 to 3 x depth	Low	1.00E-04	Surface runoff	Low	1.00E-04
Span 1 to 2 x depth	Moderate	1.00E-03	Streams	Moderate	1.00E-03
Span < depth	High	1.00E-02	Water accumulations	High	1.00E-02

Table A5: Assignment of probabilities regional stability – regional geology and stress hazards

REGIONAL GEOLOGY HAZARD			**STRESS HAZARD**		
Major lineaments	**Probability**	**Probability**	**Horizontal stress**	**Probability**	**Probability**
No lineaments	Low	1.00E-04	No known problems	Extremely low	1.00E-06
Lineament through	Moderate	1.00E-03	Minor spalling	Low	1.00E-04
			Cutter roof	Moderate	1.00E-03
			Roof failures expected	High	1.00E-02
Faults			**Adjacent mining**		
None	Extremely low	1.00E-06	No adjacent mining	Extremely low	1.00E-06
Minor faults <1m	Low	1.00E-04	Pillars adjacent	Low	1.00E-04
Moderate faults 1-3m	Moderate	1.00E-03	Stooping on one side	Moderate	1.00E-03
Major faults > 3m	High	1.00E-02	Stooping two/more sides	High	1.00E-02
Intrusions					
None	Extremely low	1.00E-06			
Minor dykes <1m	Low	1.00E-04			
Moderate dykes 1-3m	Moderate	1.00E-03			
Major dykes > 3m	High	1.00E-02			

Table A6: Example of risk rating – Single-seam pillar recovery

Pillar Recovery - Stability Risk Assessment					
Mine:	Single seam example				
Panel:	Test panel 1	Seam:	2A	Date:	12/9/00
Risk rating	**70**				
Risk level	**Risky**				
Total probability of failure	**1.52%**				
Risk factor	Assessment	Probability	Description		
PILLAR INSTABILITY		0.011	High probability		
Pillar age	10 to 20 years	0.001			
Pillar scaling	Minor	1.00E-04			
Pillar discontinuities	Minor cleats	1E-04			
Factor of safety	1.3 to 1.6	0.01			
ROOF INSTABILITY		0.000301	Low probability		
Age of workings	10 to 20 years	1E-04			
Roof conditions	Minor failures	1.00E-04			
Discontinuities in roof	Minor joints	1E-04			
Roof composition	Sandstone > 1m	1E-06			
FLOOR INSTABILITY		0.0011109	Moderate probability		
Age of workings	10 to 20 years	1E-04			
Floor composition	Laminated SST&Shale	1E-05			
Presence of water	Wet	0.001			
Floor undulations	None	1E-06			
MULTI-SEAM INSTABILITY		0.00000	No risk		
MULTI-SEAM MINING ABOVE GOAF		0	No risk		
Seam separartion		0			
Goaf consolidation		0			
Remnant pillars		0			
MULTI-SEAM MINING BELOW GOAF		0	No risk		
Seam separation		0			
Goaf consolidation		0			
Remnant pillars		0			
Hydrological hazard		0			

MULTI-SEAM PILLAR FAILURE		0	No risk		
Other seam age		0			
Factor of safety other seam		0			
Superposition		0			
Other seam barriers		0			
PARTING INSTABILITY		0	No risk		
Parting thickness		0			
Parting composition		0			
CAVING HAZARD		0.0011009	Moderate probability		
Dolerite sills	No dolerite	1E-06			
Sandstone beams	10 - 20m sandstone	1E-04			
Panel span/depth ratio	Span 1 to 2 x depth	0.001			
SUBSIDENCE HAZARD		0.0011998	Moderate probability		
Subsidence mode	Depth 10 to 100 x height	0.001			
Surface usage	Agriculture	1E-04			
Hydrology	Surface runoff	1E-04			
REGIONAL GEOLOGY HAZARD		0.000201	Low probability		
Major lineaments	No lineaments	1E-04			
Faults	Minor faults <1m	1E-04			
Intrusions	None	1E-06			
STRESS HAZARD		0.0002	Low probability		
Horizontal stress	Minor spalling	1E-04			
Adjacent mining	Pillars adjacent	1E-04			

Table A7: Example of risk rating – Multi-seam pillar recovery

Pillar Recovery - Stability Risk Assessment					
Mine:	Multi-seam example				
Panel:	Test panel 2	Seam:	2A	Date:	12/9/00
Risk rating	**74**				
Risk level	**Risky**				
Total probability of failure	**2.65%**				
Risk factor	Assessment	Probability	Description		
PILLAR INSTABILITY		0.011	High probability		
Pillar age	10 to 20 years	0.001			
Pillar scaling	Minor	1.00E-04			
Pillar discontinuities	Minor cleats	1E-04			
Factor of safety	1.3 to 1.6	0.01			
ROOF INSTABILITY		0.000301	Low probability		
Age of workings	10 to 20 years	1E-04			
Roof conditions	Minor failures	1.00E-04			
Discontinuities in roof	Minor joints	1E-04			
Roof composition	Sandstone > 1m	1E-06			
FLOOR INSTABILITY		0.0011109	Moderate probability		
Age of workings	10 to 20 years	1E-04			
Floor composition	Laminated SST&Shale	1E-05			
Presence of water	Wet	0.001			
Floor undulations	None	1E-06			
MULTI-SEAM INSTABILITY		0.01139	High probability		
MULTI-SEAM MINING ABOVE GOAF		0	No risk		
Seam separartion		0			
Goaf consolidation		0			
Remnant pillars		0			
MULTI-SEAM MINING BELOW GOAF		0	No risk		
Seam separation		0			
Goaf consolidation		0			
Remnant pillars		0			
Hydrological hazard		0			
MULTI-SEAM PILLAR FAILURE		0.0111878	High probability		

Other seam age	More than 20 years	0.001			
Factor of safety other seam	Less than 1.3	0.01			
Superposition	Partial superposition	1E-04			
Other seam barriers	Barriers = pillar width	1E-04			
PARTING INSTABILITY		0.0002	Low probability		
Parting thickness	> Bord width	1E-04			
Parting composition	Shale/mudstone	1E-04			
CAVING HAZARD		0.0011009	Moderate probability		
Dolerite sills	No dolerite	1E-06			
Sandstone beams	10 - 20m sandstone	1E-04			
Panel span/depth ratio	Span 1 to 2 x depth	0.001			
SUBSIDENCE HAZARD		0.0011998	Moderate probability		
Subsidence mode	Depth 10 to 100 x height	0.001			
Surface usage	Agriculture	1E-04			
Hydrology	Surface runoff	1E-04			
REGIONAL GEOLOGY HAZARD		0.000201	Low probability		
Major lineaments	No lineaments	1E-04			
Faults	Minor faults <1m	1E-04			
Intrusions	None	1E-06			
STRESS HAZARD		0.0002	Low probability		
Horizontal stress	Minor spalling	1E-04			
Adjacent mining	Pillars adjacent	1E-04			

Appendix 6: Review of underground pillar extraction mining methods in New South Wales

Introduction

Pillar extraction is practiced widely in New South Wales, Australia and the Northern Appalachians in the United States of America. The average height of the operations of the coal seams mined by means of pillar extraction in the USA are less than 1.5 m, whereas the operations in New South Wales are more similar, in terms of the thickness and depths of the seams mined, to those encountered in the Witbank and Highveld coalfields. A study tour of seven underground coal pillar extraction sites was conducted in New South Wales, based on the premise that better comparisons could be drawn from these thicker seam operations than the thinner seams of the USA. The operations visited were of varying depth and conditions and this chapter is dedicated to the findings of the variety of methods utilised, with a focus on identifying specific or unique practices that can be adopted or adapted for underground pillar extraction mining in South Africa.

History of pillar extraction in Australia

Australia has a long history of pillar extraction dating back more than 60 years, with its associated development of major technologies shown in Table 0–1.

Table 0–1 History of pillar extraction developments in Australia (after Shepherd & Chaturvedula, 1991, with additions by the author)

Dates	Mining Method Changes
1938	Loading machines first used in pillar extraction, but withdrawn in early 1942
Pre-1942	"Open-ended lifting" carried out working multiple (10) places with diamond shaped pillars.
1949	Modified Old Ben system tried at Bellbird Colliery (Cessnock).
1954	Coal cutters permitted in "Open-ended lifting".
1955	Joy continuous miners first introduced.
1957	First shuttle car introduced at Wongawilli Colliery and at Kerima Colliery. The first use of long (100 m) splits on 25 m centres working a diamond-shaped layout without shuttle cars.
1958	Modified Old Ben system used in State mines south of Lake Macquarie.

1957-1961	Initial attempts at Wongawilli and Nebo Collieries to work a long fender system (precursor to the Wongawilli system) and "split and lift" with continuous miners and shuttle cars were unsatisfactory.
1961	First successful Wongawilli system panels worked at Wongawilli and Nebo Collieries.
Post-1961	Continued improvement of the Wongawilli system especially with regard to split centre dimensions.
Late-1980's	Modified Wongawilli systems developed by driving splits on each side of the panel headings and lifting left and right from the splits.
Mid-1990's	Successful use of pillar stripping at Endeavour and Cooranbong Collieries for partial extraction.
Early- 2000's	Successful application of pillar stripping at Clarence, Munmorah & Cooranbong Collieries for partial extraction and at United Colliery for full and partial extraction.

Current pillar extraction operations in new South Wales

This section presents the observations of the full and partial pillar extraction operations visited in New South Wales. Information was obtained from five full pillar extraction operations and three partial pillar extraction operations.

Full pillar extraction operations

There were five full pillar extraction operations in New South Wales at the time of the visit. Four of these were visited, while information on recent experience with full pillar extraction was obtained from the fifth operation. The observations made at each of these operations are detailed here including, but not limited to, factors such as mining method, mining equipment and unique features of the operation.

Bellambi West

The Bellambi West Mine is the only pillar extraction operation of the Southern Coalfield in New South Wales. It is situated on the Picton Road to the west of Wollongong (Figure 0–1). The high grade Bulli Seam is mined which yields a hard coking coal with a low ash, low to medium volatile matter content, low sulphur and high rank which is suitable for both the domestic and export market. The coal produced from this colliery is all exported through the Port Kembla loading facility at Wollongong.

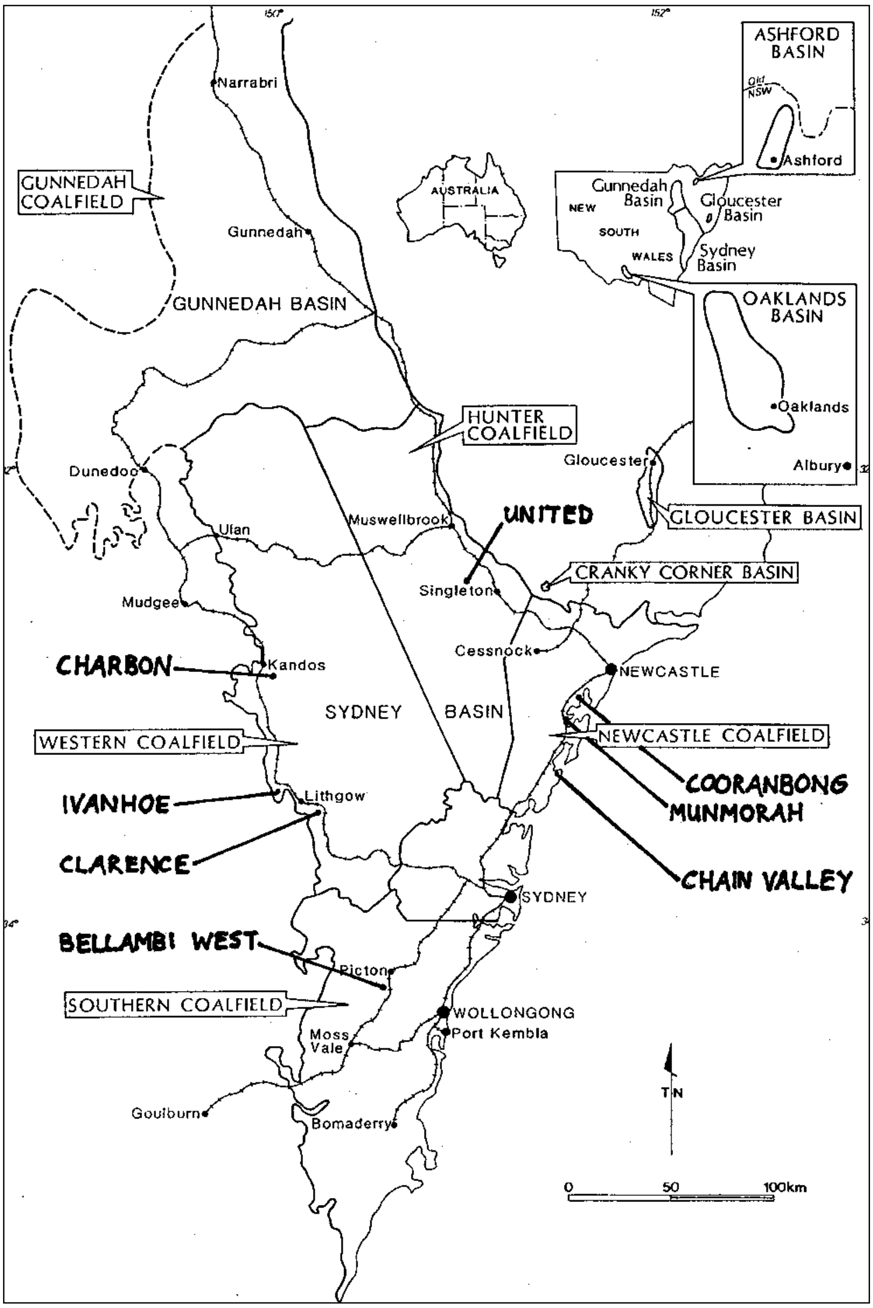


Figure 0–1 Location of Bellambi West Colliery

The mine does not usually practice pillar extraction as its major production source comes from longwalling. The previous owners sold off the mine citing floor heave and poor roof conditions for their future planned longwall panels as the reason for the sale. The new owners identified these roof and floor problems as being limited in extent and began developing for new longwall panels in the same area where these poor conditions were previously encountered. No further problems associated with roof or floor have to date been encountered. To sustain cashflow and demand for their product while longwall development was taking place, it was decided to extract a series of chain pillars in two separate areas of the mine. These panels served as travelling ways for the previously mined longwall panels and were thus not specifically designed to be extracted. The panel layouts thus were generally irregular and were also situated between two goaves. A modified

Wongawilli split and lift method of double-sided extraction with Articulated Breaker Line Supports (ABLS's) was used in both sections, as the chain pillars were of significant size and strength to support this mining method. The extraction panels had barrier pillars 32 m wide separating them on either side from the goaves. Both panels were extracted in a manner as depicted in Figure 0–2.

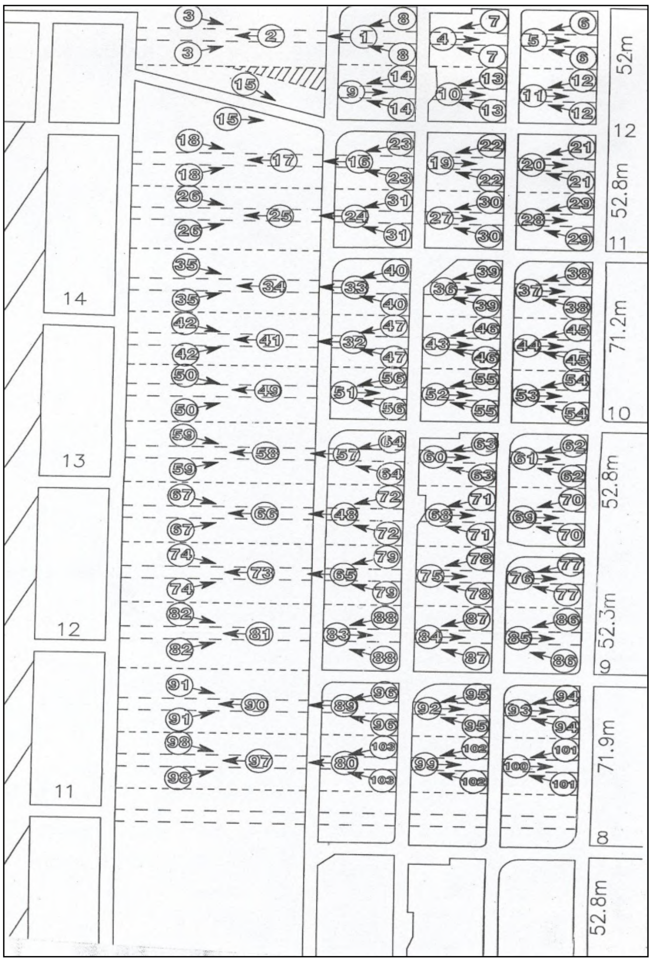


Figure 0–2 Pillar extraction sequence at Bellambi West Colliery

The typical lifting operation is shown in Figure 0–2 with approved variations also used. Snooks were left as shown in Figure 0–3, although these were sometimes split to encourage goafing to closely follow the extraction line.

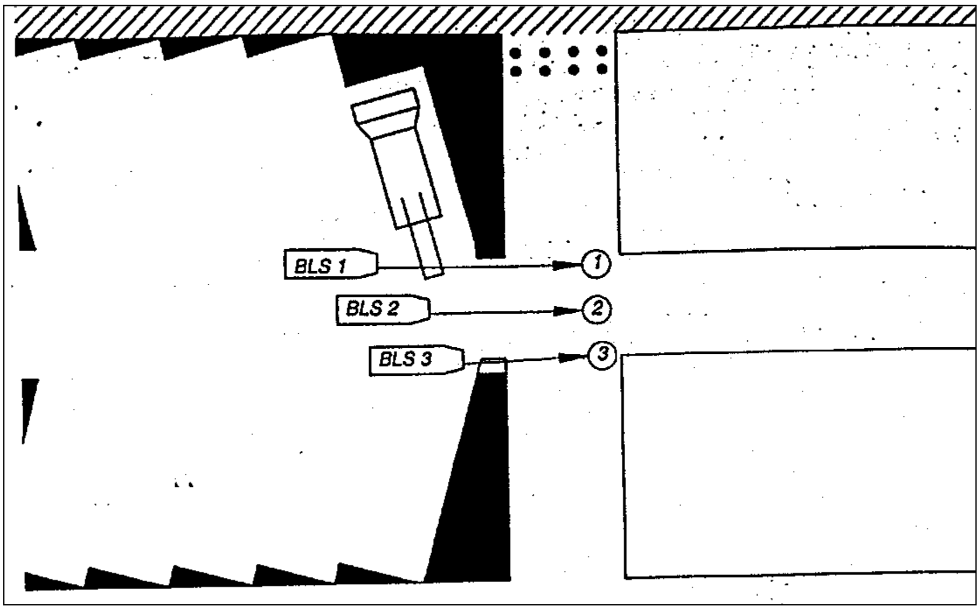


Figure 0–3 Split and lift pillar extraction operation at Bellambi West Colliery

The splits were driven (as shown in Figure 0–2) to a maximum of 15 m before being supported with a Fletcher roofbolter which places four 1.5 m point anchor pre-tensioned bolts with straps per row, with the rows spaced a distance of 1.2 m apart. The bord widths in all instances were an average of 5.5 m. Once bolted, the split was holed and supported before lifting back of the newly created 12 m wide pillars took place. The panels were operated with remote controlled continuous miners (a Joy 12CM11) with two Joy 15SC shuttle cars, each with an approximate 15 tonne capacity. Three Eimco Articulated Breaker Line Supports (ABLS's) operated by remote control were employed. Each of the ABLS's provided a maximum support load of 480 tonnes and were positioned as shown in Figure 0–3, with the middle ABLS required to follow the centre line of the roadway. The ABLS's, however, were not set to their maximum load as this may have resulted in the premature fracturing of the roof. Generally they were set to approximately one third of their maximum load, which equated to approximately 160 tonnes. The ABLS's were moved forward a maximum of 2 m each at any one time and only one at a time. They were set to the roof after each move forward before being moved again. They were spaced a maximum of 2 m from each other and kept as close to the continuous miner and solid fender as possible (as shown in Figure 0–3). In addition to the ABLS's, timber breaker lines were also used as ancillary support.

The average production form these two extraction panels was approximately 60,000 tonnes per month whereas the longwall development panel produced an average of 35,000 tonnes per month. There were eight personnel (detailed in Table 0–2) operating per shift in the extraction panels operating on a three shift per day basis, five days per week. This was two persons less than the longwall development panel where there were two dedicated roofbolt operators.

Table 0–2 Employees per extraction panel at Bellambi West Colliery

1	Continuous Miner Operator
1	Cable Handler
2	Shuttle Car Drivers
2	Artisans (double up as utility personnel)
1	Section Miner
1	Shift Boss

No variations in the coal quality or size grading were noted when compared to that of the longwall development section. The average mining height of both extraction panels was 2.7 m situated at an average depth of 420 m below surface. The extraction operations were 10 m above the 1.5 m thick Balgowrie Seam and 30 m above the 10 m thick Wongawilli Seam. Neither of these seams had previously been mined, nor was there any intention of exploiting them at any point in the future. Roof spalling of approximately 1 m was recorded in the approximately six-year-old panels, consisting of four roadways each. The roof consisted of sandstone with interbedded shales and the floor consisted of shale and the coal seam was intruded by stone rolls and stringers which caused inherent weaknesses to the pillars, which required that the ribsides be supported with straps with sidewall spalling of 1 – 2 m being recorded. The panels were force ventilated with ducting and returned through the old goaf previously created by the longwalls. No reports of spontaneous combustion or incidents of methane accumulations have to date been recorded at Bellambi West Colliery. The overall surface subsidence was expected to be approximately 400 mm. Abnormal pillar behaviour in one panel necessitated a layout change from that shown in Figure 0–4 to that shown in Figure 0–2. The layout in Figure 0–4 was irregular, which created irregular goafing patterns and resulted in the goaf hanging up. Further complications in not achieving the critical width for goafing pre-empted the layout change, which minimised the risk of a strong goaf that may have caused featheredging into the working face.

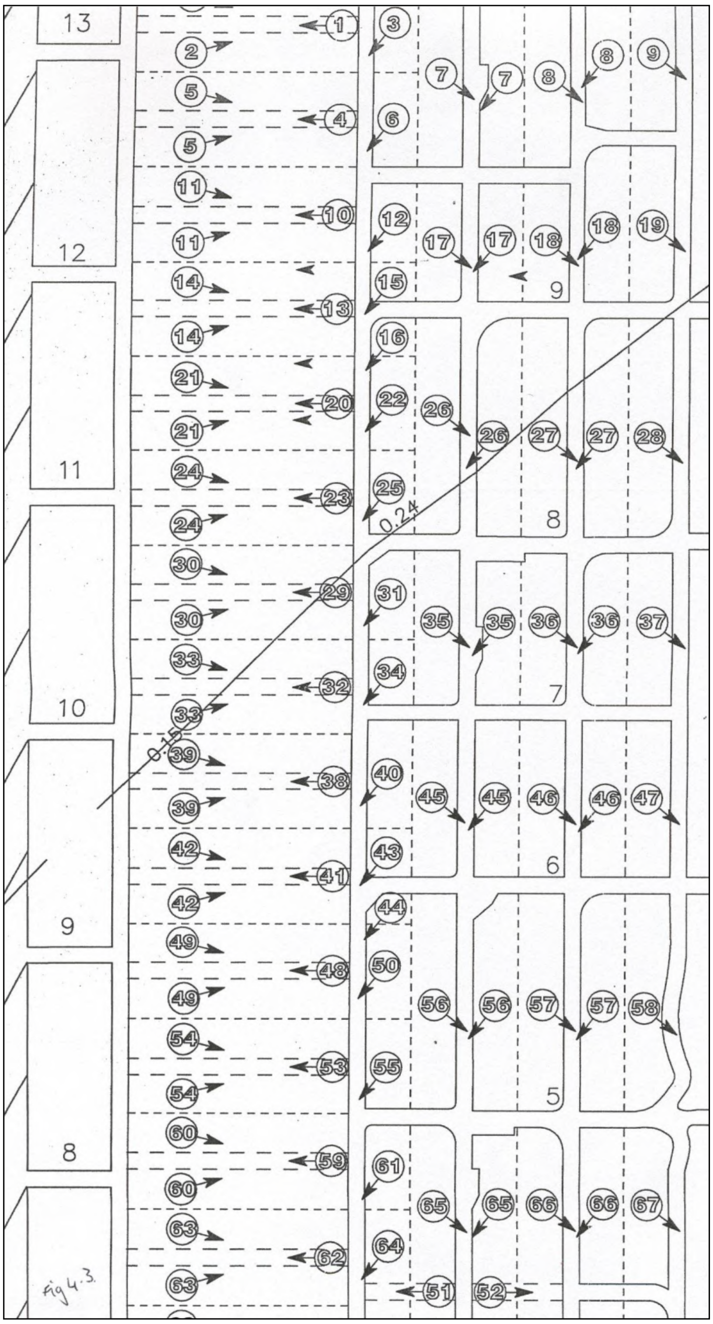


Figure 0–4 Original pillar extraction sequence at Bellambi West Colliery

One fatality has occurred while conducting this pillar extraction operation. No details as to the exact nature of the fatality were available, except that it was associated with a roof fall while attempting to reset the continuous miner that had tripped under unsupported roof. A code of practice together with specialised training of the personnel was conducted before the extraction started. No information pertaining to the costs of the operation could be made available as a result of confidentiality of the information.

Charbon Colliery

Charbon Colliery is located in the Western Coalfield near the town of Kandos, some 250 km northwest of Sydney (see Figure 0–5).

Figure 0–5 Location of Charbon, Ivanhoe and Clarence Collieries

The Lithgow seam is mined which has a medium to high volatile matter, medium to high ash and low sulphur. All production from Charbon Colliery is exported via rail to the Port Kembla loading facility at Wollongong. The Lithgow seam is generally 2.7 m thick with local variations of the thickness by a few centimetres caused by an overseam dirt band. It is the only seam mined, and is situated 4.5 m below the Lidsdale seam that has a thickness of 100 mm. The overlying strata consist of bands of claystone, mudstone and sandstone (which are considered to be weak) and the floor consists of shales and tuff (which are generally considered strong). The depth of cover to the Lithgow seam varies from 190 m at the centre of the mining lease to 30 m at the extreme inbye end of the panel and outcrops on the perimeter of the mountain that overlies the deposit. Two clay bands exist within the coal seam, which expand when wet. These bands do not effect the mining operation however.

A modified Wongawilli split and lift full pillar extraction method is used which is limited to the 30 m cover line to prevent damage to the mountainside. Beyond the 30 m cover line only partial extraction without caving can occur by means of the creation of small pillars (between 16 m and 20 m square) by usual bord and pillar mining techniques. Generally, for the full extraction panels, a panel is developed out some 650 m with three headings at 40 m centres with crosscuts (splits) being driven at 50 m centres to create 3-way and 4-way intersections. This initial development, once complete, leaves the final extraction panel usually consisting of 14 splits. A barrier pillar of 40 m width is left between extraction panels. From the 6th crosscut onward, a 25 m split between the headings on the solid side of the panel is done (i.e. the headings farthest from the previous goaf) to facilitate better ventilation and shuttle car wheeling arrangements. In addition to these splits, "run-outs" are driven from the heading closest to the goaf side from every third crosscuts to hole through into the previous goaf to facilitate control against any inrushes of water and/or gas into the workings from the previous goaf. The primary purpose of the 3 heading development system used at Charbon Colliery is to reduce the number of 4-way intersections formed during the development phase. Previous extraction panels had experienced roof problems associated with the 4-way intersections, which had to be supported using expensive cable trusses.

The 5.5 m wide roadways are formed by either a Joy 12CM12 or Joy 12CM11 (both remote controlled) and are supported with four 2.1 m full column resin supported roofbolts installed per row with a strap, spaced 1.8 m between the rows. The roofbolting operation is done using an on board bolting system. Two 15 tonne capacity Joy 15SC shuttle cars are used to produce approximately 14,000 tonnes per month on development.

The pillar extraction process is shown in Figure 0–6. Upon completion of the development as described previously, the extraction process begins with the pillar furthest inbye on the goaf side being split and supported along its 25 m centre to create pillars that are nominally 20 m wide. These splits are supported with four 1.8 m full column resin supported roofbolts installed per row with a strap, with the rows spaced 1.8 m apart. The roofbolting operation is again conducted using an on board bolting system. The use of shorter roofbolts (as opposed to those used during development) is based on the premise that the roadway will only stand for a short duration prior to extraction. Three remote controlled Voest Alpine ABLS's are then used in this left and right lifting of the fenders in the manner shown in Figure 6. The ABLS's are advanced one at a time to a maximum of 2 m at any one time before being set to the roof and are spaced a maximum of 2 m apart. The middle ABLS is required to follow the centre line of the roadway.

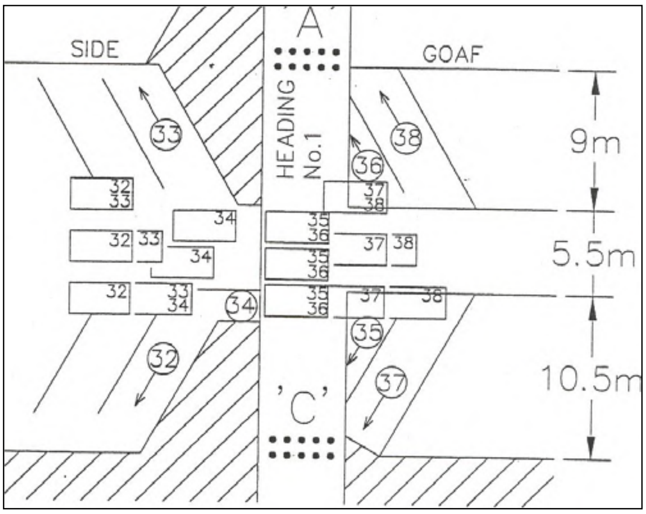


Figure 0–6 Modified Wongawilli split and lift operation at Charbon Colliery

In addition to the use of ABLS's, timber breaker props consisting of two rows of 5 props each are set in each of the headings, with only one row being set in the heading furthest from the goaf. In this way extraction takes place in a straight line extending from the previous goaf line. The roof bolting rigs are removed from the continuous miner prior to lifting. The maximum lift taken is approximately 9 m into the previous goaf side and approximately 10.5 m into the solid side. Thus only half the pillar is extracted per lift into the solid side, although the lifts into the goaf side will hole into the previous goaf. The angle of lifting is between 60° and 70° and the lifts are cut the width of the continuous miner cutter head (approximately 3.6 m). The ABLS's are moved as shown in Figure 0–6 and are set to the roof with a pressure of one third its maximum loading capacity (known locally as the edge of the "green zone"). When they start to take load, the gauge moves into the "yellow zone", indicating that the roof is settling. At this point the ABLS's are moved forward and thus closer to the solid fenders to limit the span across which the goaf could featheredge and in so doing also provides greater protection for the continuous miner driver. Snooks are left as shown in Figure 0–7, with the snooks closest to the solid side of the panel being 10 m wide to ensure that a roadway remains open for return ventilation of the panel. This extraction process continues across the intersection toward the solid side of the panel and once completed the sequence starts again with the driving of a split through the pillar closest to the goaf side and lifting back toward the solid across the intersection toward the solid side of the panel. The lifting operation on a per shift basis produces more than the development operation, as less roofbolting is required by this operation.

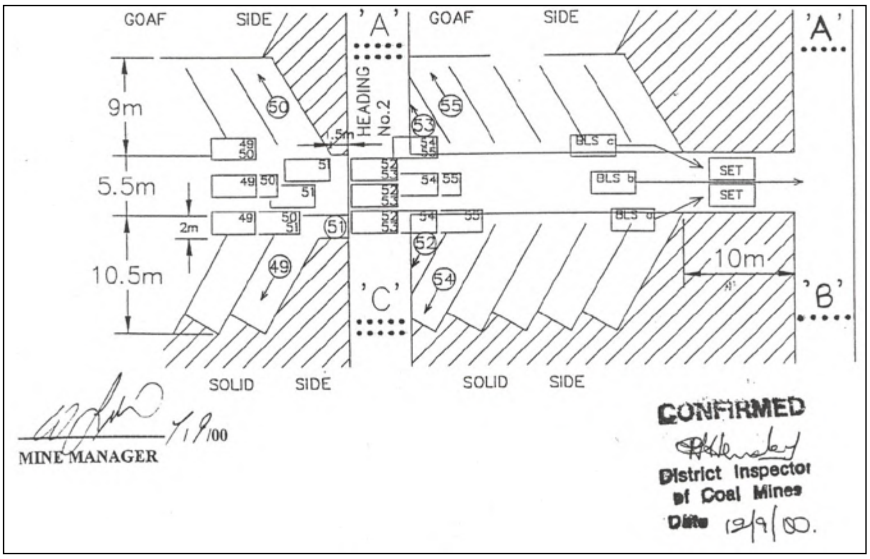


Figure 0–7 Leaving of snooks during extraction operation at Charbon Colliery

The breakdown of personnel at Charbon Colliery is shown in Table 0–3.

Table 0–3 Employees per extraction panel at Charbon Colliery

5	Machine Operators
2	Artisans
1	Section Miner

In general, no adverse effects were reported with this operation. Thirteen panels to date have been extracted using this method of mining. Rib spalling was noted during the lifting off operation that was associated with a weight transfer from the previous goaf to the solid pillars outbye of the goaf. Surface subsidence was noted, although this could not be accurately recorded due to the nature of the mountainous surface. Some CO_2 emissions were recorded which were associated with the overlying Lidsdale seam being broken during goafing. Little effect of windblasts has been reported, although precaution is taken when an extended goaf has not taken place.

The continuous miner has been buried on two previous occasions with no loss of life or injury. An electrical breakdown in the last lift was the cause of one of the burials when the snook was unable to provide adequate support for the roof cantilever, and the other was attributed to a geological anomaly and the presence of an aquifer in the immediate roof of the panel being worked. The ABLS's were buried on one occasion, attributed to the hanging of the goaf for a prolonged period of 5 weeks causing a violent goaf to overrun them.

No indication of the operating costs of the operation were made available due to confidentiality of the information, but it was inferred that it was one of the lowest cost operating mines in the region as a result of the long distance which has to be covered to transport the product to export facility at Wollongong.

An interesting observation at this colliery was the use of a monorail system to suspend the continuous miner's power cable and water hose from the roof. This system reduces the hazard of the cables being damaged by rib spall and also reduces the risk of back injury to the personnel. It was reported that the loss of production from damage to the cables had been significantly reduced since the inception of the monorail system.

Ivanhoe Colliery

Ivanhoe Colliery is a 200,000 tonne per year producer situated in the Western Coalfield near the town of Lithgow, some 150 km west of Sydney (Figure 0–5). All of the coal produced from this colliery is consumed by a nearby power station. It is a full pillar extraction operation, mining the Lithgow and Lidsdale seams that are separated by a 15 – 20 cm thick clay intrusion. The operation lies 10 m below the Irondale seam, which is unmined. This 10 m separation consists of sandstone and mudstone layers. Two sections operate on a single shift basis, one of which is the pillar extraction panel, and the other a preparation panel for future pillar extraction. Both sections operate with a section miner and five machine operators with a total of 20 people employed.

The mine has been in operation since the early part of the 20th century when large areas were developed by the bord and pillar method of mining approximately 60 m below surface. At the time of this primary development, the bottom 1.5 m horizon of the 2.7 m thick coal seam was mined by drill and blast methods, to create bord width approximately 5 m wide, with no support of the roof or ribsides being conducted at that time. Some limited split and quarter extraction of these pillars subsequently took place in some areas of the mine at various stages during the mines life. A recent decision made by the current owners to fully extract certain areas of the mine has prolonged the life of the mine by an estimated 3 years. The process of extraction is preceded by panel rehabilitation, which takes the form of brushing top coal to the full seam height of previously developed areas and installing two 1.8 m long resin roof bolts in a row, which are 2 m apart. A remote controlled Joy 12CM11 continuous miner with two 15 tonne capacity Noyes Hydrocars performs this rehabilitation function. The roofbolting is conducted with a custom designed roofbolter. Production from the preparation panel is variable and low, as limited areas exist for future pillar extraction. Also, the areas being prepared for pillar extraction have varying physical conditions, with previous roof falls into the intersections being one of the largest problems, rendering many areas inaccessible. CO_2 is also a problem as a result of a lack of ventilation through these old areas. Once rehabilitation is complete, the extraction of the pillars can commence. The layout as shown in Figure 0–8 shows the current extraction panel at the colliery.

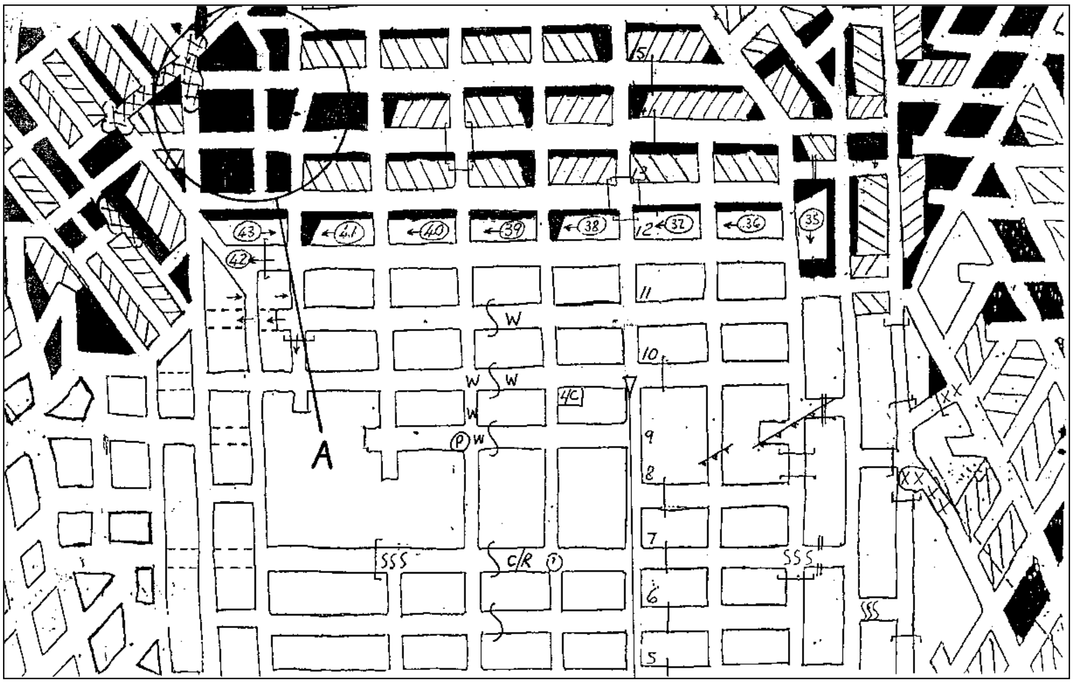
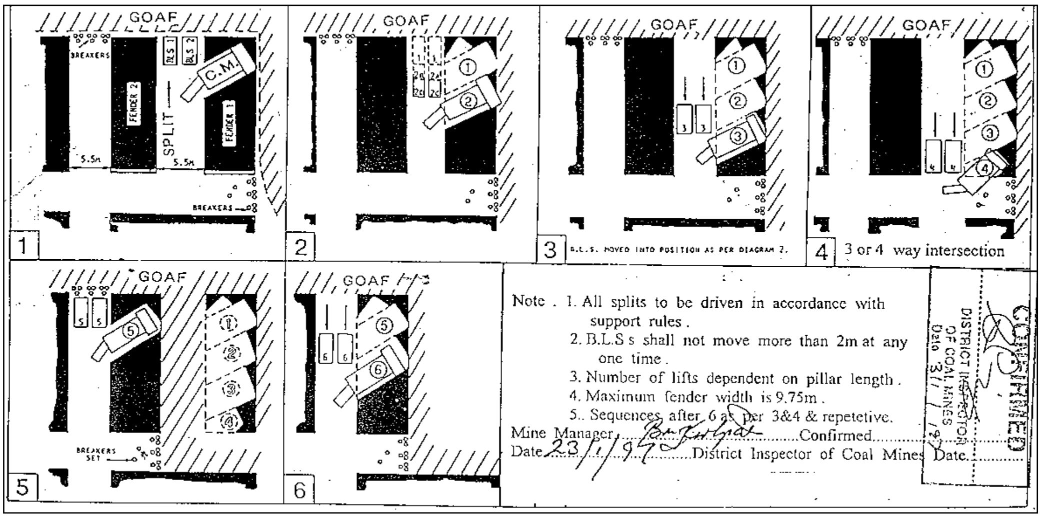


Figure 0–8 Pillar extraction sequence at Ivanhoe Colliery

Although the mine has approval for single and double sided lifting of the pillars, Ivanhoe utilises only the single sided lifting process with a remote controlled Joy 12CM11 continuous miner, two 15 tonne Noyes Hydrocars and two remote controlled Voest Alpine Breaker Line Supports (ABLS's). A third ABLS would be used if double sided lifting were to be utilised. The ABLS's are advanced a maximum of 2 m at any one time and can only be moved one at a time. They are spaced a maximum distance of 2 m apart to reduce the overall span of the roof. A method of extraction similar to that shown in Figure 0–9is currently used.



Note . 1. All splits to be driven in accordance with support rules .
2. B.L.S s shall not move more than 2m at any one time .
3. Number of lifts dependent on pillar length .
4. Maximum fender width is 9.75m .
5.. Sequences after 6 as per 3&4 & repetetive.

Mine Manager.....................Confirmed.....................
Date 23/1/97.........District Inspector of Coal Mines Date.............

Figure 0–9 Approved pillar extraction utilising ABLS's at Ivanhoe Colliery

The pillars are extracted from right to left as shown in Figure 0–9 with the approximately 25 m long by 10 m wide pillars lifted a maximum 9 m into the pillar, thus leaving a thin fender as protection for the working face and as an indicator as to the status of the roof activity. It was noticed that the coal was very friable and as a result was cut easily. The ABLS's were set to only 25 percent of their maximum loading capacity so as not to fracture the roof. The area being extracted was under stress as evidenced by the row of pillars behind the extracted row spalling to such an extent that the pillars were surrounded by rib spall reaching between one third and one half the height of the pillar, with the extent of the spalling being approximately 0.5 m as noticed from marks on the roof. This was probably a result of high abutment stresses from the irregular mining layout negatively affecting the already aged pillars. An inference to cause of this spalling is the fact that the lower part of the pillar slabbed approximately 30 cm as a result of time effects and having being formed by drill and blast methods (Madden, 1987). This lower area would have created a situation whereby the upper portion of the pillar slabbed as a result of having no support from the already slabbed bottom portion of the pillar.

The area is overlain by State forest and, although subsidence has been noted, it is not a legal requirement for subsidence to be measured. No indication as to the safety history or costs of the operation could be made available, as this information was confidential.

United Colliery

United Colliery is situated in the Hunter Coalfield approximately 90 km west of Newcastle and 25 km south west of Singleton (Figure 0–1). The operation is just over 10 years old and produces approximately 2.2 million tonnes of ROM coal from three production sections, all of which is exported through the Newcastle ports to customers in Asia. Mining is undertaken in the Woodlands Hill Seam, making United Colliery the deepest operation in the area at approximately 250 m below surface at its current workings. The seam dips in a northwest to southeast direction from 40 m below surface at the drift shaft complex to approximately 220 m at the current workings and it is intersected normally to the dip direction by a number of fault planes. United Colliery is overlain by a series of coal seams, the closest of which lies 170 m above the Woodlands Hill Seam. These upper seams are mined using open cast methods and the caving activity associated with the current pillar extraction panel at United Colliery does not affect these surface operations. The seam height of the area varies from 3.2 m – 3.6 m with the mining height generally being 3.2 m. The immediate roof consists of approximately 0.3 m of coal, which is overlain by a 3 m band of shales and mudstones and then by a layer of competent sandstone, which is approximately 2.5 m thick. The floor consists primarily of mudstone with some laminations. The lease area of the mine is bounded by a number of dykes and severe fault zones that have dictated the length and layout of the six extraction panels. A decision by the new owners in May 2001 to operate seven longwall panels upon completion of the current and final 415 pillar extraction panel will leave the mine with approximately seven years production.

Full extraction has taken place at the colliery since its inception although the latter panels are a combination of full and partial extraction techniques. Panels of various sizes (as a result of the geological boundaries) ranging from 5 – 9 road headings have been employed to varying degrees of success. The initial extraction panels close to the drift shaft complex were shallower than the later panels and these operated in generally better conditions than the later, deeper panels. In these initial panels all the pillars were extracted, whereas the layouts and extraction sequences of the later panels had to be changed to account for the effects of depth as well as the dip of the seam that created unusual stress regimes on the left hand side of each of the panels. In these instances the centre line of pillars were left standing to reduce the overall span of each panel. Apart from leaving this centre line of pillars, the fenders were only partially extracted in some areas, creating a situation of full and partial extraction techniques within the panel.

The current panel being extracted was driven using a 9 road heading layout (approximately 245 m wide), creating pillars 40.5 m long by 30 m wide and utilising a remote controlled Joy 12CM12D continuous miner and three 15 tonne capacity Joy 15SC shuttle cars. Halfway along the 2,500 m long panel, the pillars were increased in size to 45 m long to 32.5 m wide to account for changing stress conditions resulting from the increase in depth. The average bord width was 5.4 m. 30 m wide barrier pillars separate the panels and these were not extracted as the panels were sealed upon completion of the extraction process. The roof was supported systematically with a twin boom Fletcher roofbolter installing rows of four 2.1 m long fully encapsulated roof bolts, with the rows being 1.4 m apart. At intersections the support density increased to five 2.1 m bolts, with the rows 1.1 m spaced apart. Rib spall was a serious problem (particularly at the pillar edges), which required support (with meshing in some areas). Further, the ventilation of the panel was split and use was made of ventilation ducts to force the ventilation into the section. Upon completion of the development, the pillars were extracted in a manner as shown in Figure 0–10.

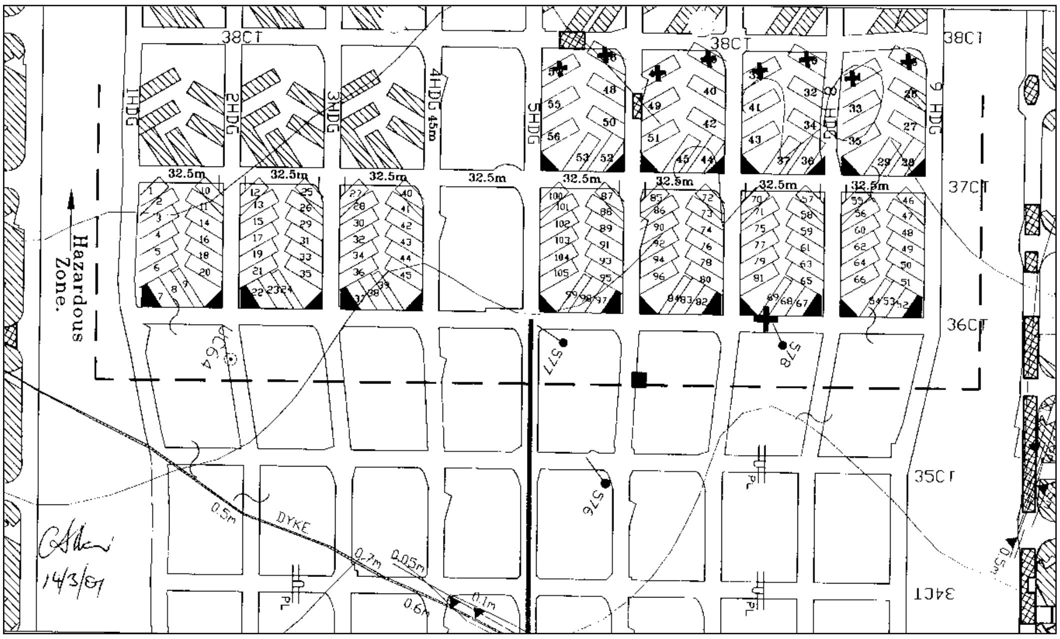


Figure 0–10 Extraction layout at United Colliery

The pillars are lifted on a single and double-sided basis using two and three remote controlled Jeffrey ABLS's respectively (set to 200 tonnes) with timber props set as ancillary support. The ABLS's are limited to advance one at a time to a maximum of 2 m at any one time and set to the roof. They are also set to a maximum distance of 2 m apart and the middle ABLS is required to follow the centre line of the roadway when all three ABLS's are used. The remote controlled continuous miner is modified with the cutter head being reduced from 5.4 m wide on development to 3.6 m wide on extraction. Three 15 tonne capacity shuttle cars are used during extraction. The fenders are lifted at 60° and are cut to a maximum depth of 12 m to create a system of snooks and small fenders as those shown in Figure 0–10. The pillars are a maximum age of two years at the time of extraction, with the outbye pillars being the oldest.

This system of extraction yields approximately 1,350 tonnes per shift. There are 12 production shifts per week on a three shift per day cycle. The remaining three shifts are used for maintenance and panel work (e.g. belt retractions, rerouting of ventilation ducting, etc.). The two development panels each produce approximately 1,250 tonnes per shift, working on the same shift basis as the extraction panel. The extraction panel operates with one section miner and six machine operators per shift, while the development panels each have one miner and eight machine operators (the extra manpower being required for roofbolting). The colliery operates with a total labour complement of 162.

The presence of methane increases with the increasing depth of the operation, but these higher concentrations are liberated upon development and do not pose a risk during the extraction process, although a spontaneous combustion incident occurred in Panel 415 which required that the workings up to that point be sealed and flooded before extraction could recommence. Rib spall was a common occurrence near the line of extracted pillars with rib spall in some places laying one-third the pillar height, which would indicate that the roof was settling and thus causing high abutment loads. The continuous miner and ABLS's have been buried on more than one occasion, the most recent occurring at the time of the visit. Caving generally does not progress until a number of rows of pillars were extracted. However, once caving occurs to the full height, a regular pattern of goafing closely follows the extraction line. Surface subsidence of approximately 1 m occurred over the initial workings.

Although no exact costs could be obtained, it was inferred that the cost of the extraction was approximately 70 percent the cost of a development panel as a result of a lower labour complement, the absence of need of support as well as lower consumption of continuous miner picks due to the coal being more friable on extraction.

Use of continuous haulage during pillar extraction at United Colliery

United Colliery was in a unique position to make use of a continuous haulage system to develop and extract Panel 416 during mid-2000. Panel 416 was a 5 road-heading layout developed for pillar extraction and was 143 m wide. The roadways were developed to a width of 5.4 m with the belt road (centre roadway) developed 6.5 m wide to accommodate the continuous chain haulage. The panel was approximately 250 m below surface and the pillars created were 33.3 m long and 30 m wide. As a result of increasing depth, the pillar sizes were increased to 33.3 m long by 50 m wide approximately halfway through the 3200 m long panel. The average mining height was 3.2 m. A remote controlled Joy 12CM12 continuous miner and a remote controlled continuous haulage system consisting of 5 units were utilised in a manner as shown in Figure 0–11.

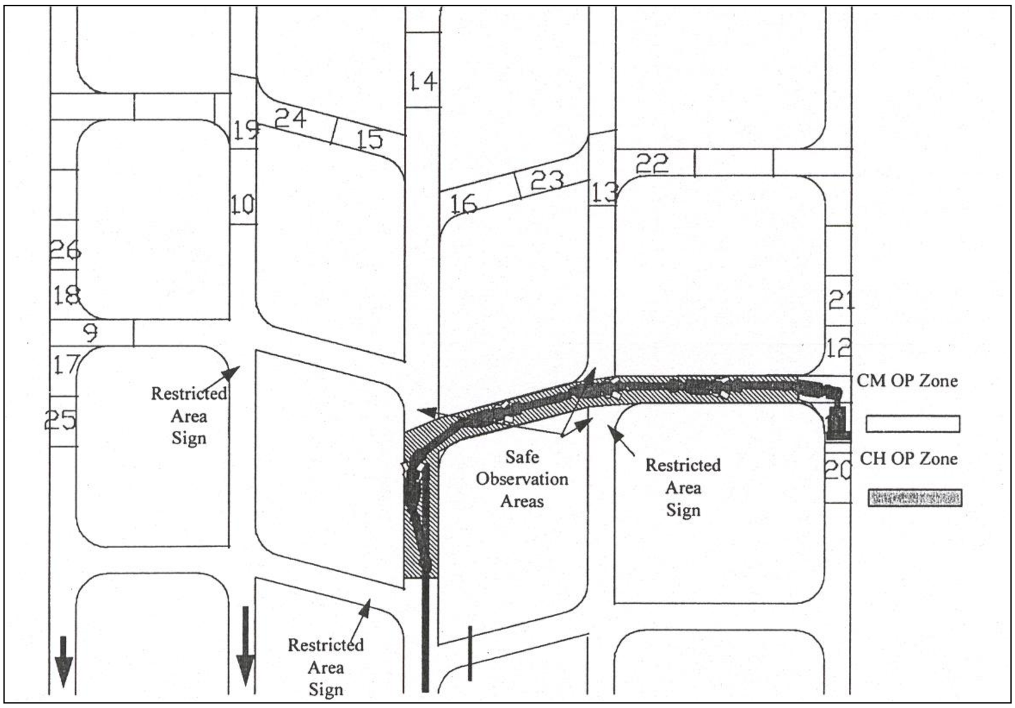


Figure 0–11 Development layout using a continuous haulage system at United Colliery

The roof was supported systematically upon development with a Fletcher roofbolter installing rows of four 2.1 m long fully encapsulated roof bolts, with the rows being 1.4 m apart. The centre roadway was supported with six 2.1 m bolts with the rows 1 m spaced apart. The ventilation of the panel was split and use was made of ventilation ducting to force ventilation through the section. One section miner and 10 machine operators were required to produce 1,700 tonnes per shift.

Once the development was completed, the pillars were extracted with one section miner and 8 machine operators in a manner as shown in Figure 0–12.

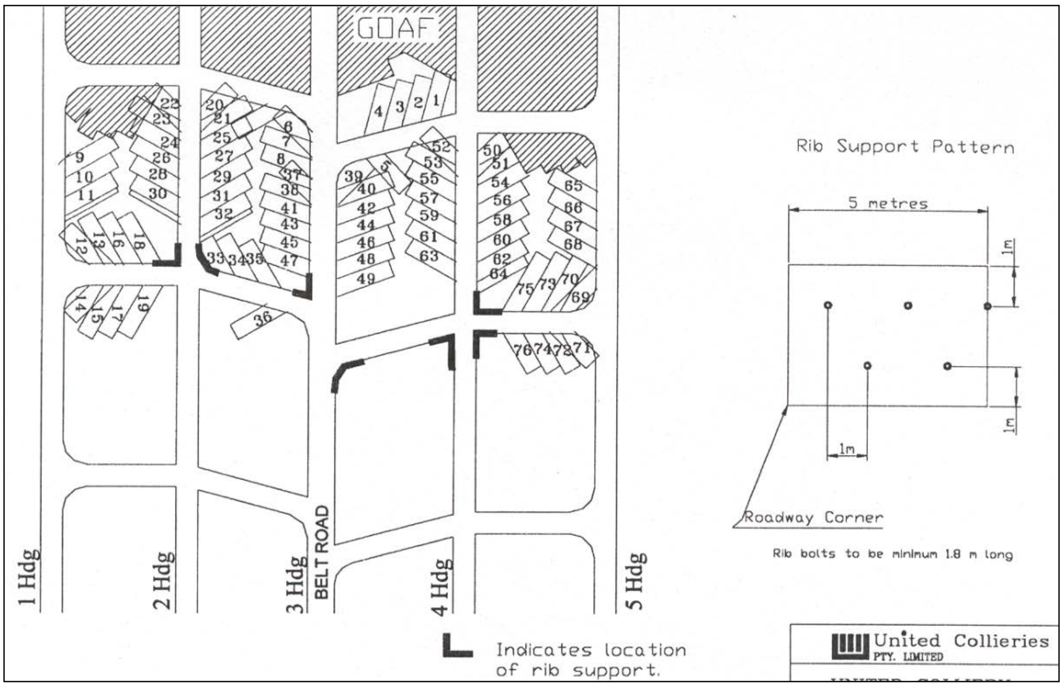


Figure 0–12 Extraction layout using a continuous haulage system at United Colliery

In addition to the modified continuous miner (with the 3.6 m wide cutter head) and continuous haulage systems, two or three remote controlled Jeffrey ABLS's were used to lift the pillars on a single and double sided basis respectively. A series of snooks and fenders were left to control goafing and goafing occurred in a similar manner as described previously. The continuous haulage obtained record productions in excess of 100,000 tonnes per month. However, there was no consistency in production as at times there would be no production for a matter of weeks associated with the following problems:

Ventilation ducting mounted on the continuous haulage and continuous miner often broke as a result of excessive vibration associated with the machinery,

Floor breaking as a result of the combined weight of the continuous miner and the 5 continuous haulage units,

Labour intensive on development,

Large increase in operating costs,

Large number of component failures as a result of modifications required in terms of the New South Wales mining legislation.

Chain Valley Colliery

Chain Valley Colliery temporarily ceased pillar extraction on 9 March 2001 and is currently on a maintenance-waiting period while the owners finalise the sale of the mine. Although the operation could not be visited, some limited information regarding its use of the full pillar extraction mining technique was obtained. Chain Valley Colliery is situated in the Newcastle coalfield and mined the Great Northern seam. It is situated on the Central Coast near the city of Newcastle (see Figure 0–1).

Full pillar extraction using a remote controlled Eimco Dash 3 continuous miner with two 15 tonne capacity Joy 15SC shuttle cars and three remote controlled Voest Alpine 650 tonne ABLS’s was conducted producing approximately 36,000 tonnes per month with one section miner and four machine operators. On development, 5 headings were developed to form pillars 35.5 m square with bord widths 5.5 m and a mining height of 2.7 m. The working seam was situated 200 m below the surface. The pillars were designed to a safety factor of 1.6 with the barrier pillars also being extracted. The roof was bolted on development with two 1.5 m full column resin bolts per row, with the rows spaced 3 m apart. The immediate roof was a 30 m thick conglomerate. The exact nature of the method of extraction could not be obtained, however it was indicated that the centreline of pillars was left during extraction to reduce the overall width of the extraction panel and to aid control of the floor, as the floor is soft and displays similar characteristics to the floor at Munmorah and Cooranbong Collieries. Further, a 0.5 m thick coal layer is left on the floor during development to further combat the soft floor complications.

Future planning for pillar extraction will be conducted using a partial pillar extraction technique not unlike the methods used at Munmorah and Cooranbong Collieries with the dual purpose of preventing full caving and maintaining the integrity of the worked Wallarah seam above which is flooded. The workings on the Wallarah seam (30 m above the Great Northern Seam) did not superimpose the extracted workings.

No adverse effects were encountered with this mining method. There was no noticeable change in the quality of the coal produced, partly because the panels extracted were never older than 12 months. There was some spalling of the sidewalls attributable to the massive conglomerate roof. Limited surface subsidence occurred during the extraction process.

Partial pillar extraction operations

Three partial pillar extraction operations were visited in New South Wales. Two of these operated under massive conglomerate roof in the Newcastle region and the third operated in the Western coalfield. All three utilised the partial extraction method for various reasons and these, together with other observations pertaining to the mining methods, are discussed here.

Clarence Colliery

Clarence Colliery produces approximately 1.2 million tonnes per year. It is situated in the Western Coalfield near the town of Lithgow (see Figure 0–5) and mines the Katoomba seam (which is an extension of the Bulli seam in the Southern Coalfield).

Clarence Colliery has a vast history of employing various pillar extraction-mining methods. Initially, only bord and pillar development mining was conducted, but it was later decided to increase the overall recovery by quartering these 30 m by 30 m pillars. This proved to be unsuccessful as a result of pillar creep problems associated with the resulting 9.5 m by 9.5 m pillars. A split and lift type operation was then employed, but the massive Triassic sandstones that overly the Katoomba seam created caving problems with the goaf hanging up over large spans. The introduction of ABLS's with use in a modified Wongawilli system again created similar problems with the goaf as a result of the massive sandstone roof. The ABLS's couldn't sustain the effects of the cantilevering effect which resulted in them being buried on numerous occasions. Longwalling was then implemented, but the lease area contains massive vertical joint sets, which extend through to the surface, which created problems of the roof breaking into the working face of the longwall, and after seven longwall panels had been mined, the mine was sold to its present owners. The new owners decided to develop a partial extraction mining technique to increase production without creating a goaf and in so doing negating the effects of the roof cantilever problems previously experienced with full extraction methods. Further, the mine pumps between 14 – 18 megalitres of water per day as a result of previous goafing of the area that broke two overlying aquifers (80 m and 160 m above the coal seam), and a partial extraction mining method without goafing would thus also limit any further problems associated with the inrush of water from these aquifers. The operation when visited was operating at a depth of 250 m below surface.

A primary seven heading bord and pillar section creating pillars 30 m by 30 m, bord widths 5.5 m and leaving barrier pillars being 42 m wide between panels. The development areas are supported with four 1.8 m full column resin bolts per row, with the rows being 2 m apart. There are two development sections operating on a two shift per day basis. One of these sections operates with a remote controlled Joy 12CM12 continuous miner, two 15 tonne capacity Joy15SC shuttle cars and a four boom Fletcher roofbolter, and produces approximately 29,600 tonnes per month with one section miner and six machine operators. The other development section is a double-header section operating with two remote controlled Joy 12HM9 continuous miners, both with on board roofbolting rigs. This section has two belt systems, one for each of the continuous miners. There are three 15 tonne capacity JoySC15 shuttle cars, one dedicated to each of the continuous miners and the third shuttle car operating on where it is needed. The rational behind this is that as one continuous miner is cutting, the other will be bolting and that at any one time there will be two shuttle cars in operation and ensuring that production is continuous and maximised. This panel produces approximately 33,000 tonnes per month and operates with one section miner and six machine operators. A 6 m thick layer of sandstone generally overlies the area and the floor consists of a 2 m thick siltstone/sandstone that is overlain by bottom coal approximately 1 m thick. The 3.7 m thick coal seam consists of interbedded mudstones with the upper 2.7 m portion of the seam being mined. An immediate 30 cm thick mudstone band in the immediate roof is common throughout the coal seam.

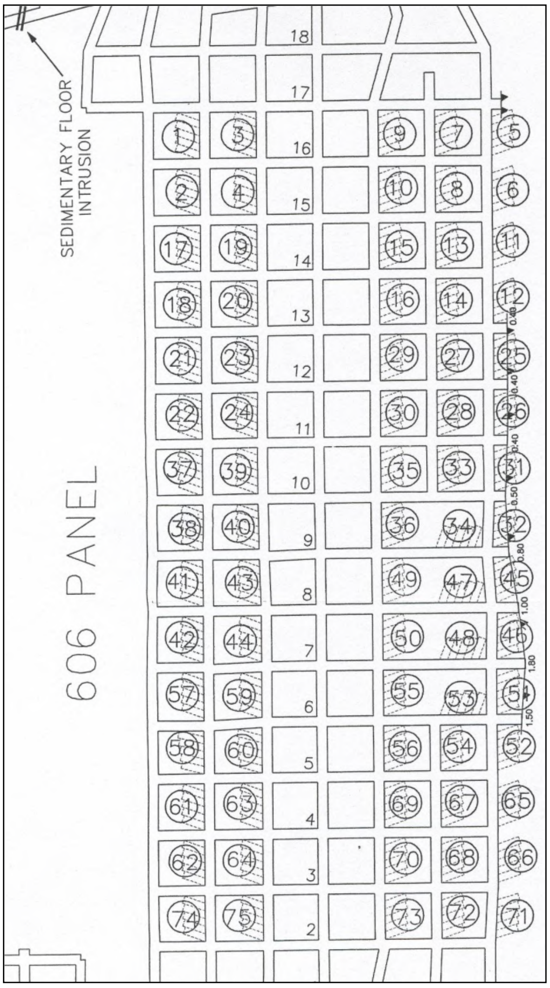


Figure 0–13 Partial extraction panel layout at Clarence Colliery

Upon completion of the development, the partial extraction is conducted in a manner as shown in Figure 0–13, stripping the interpanel barriers and the two outer rows of pillars (on one side of the pillar) to a maximum depth of 11 m using an open ended lifting approach at a cutting angle of approximately 60°. As this extraction follows development, the maximum age of the pillars is 2 years and there are no noticeable changes to the pillars at the time of extraction as compared to the development characteristics. This extraction system (as shown in Figure 0–13) is designed to a maximum of 260 m below the surface, however, when the depth below surface is below 260 m, the barrier pillars are not mined. The resultant 40 m wide barrier pillars and the two centre pillars thus remain to provide permanent support to the overlying strata with a resultant safety factor of 1.5 reduced from the original safety factor of 2.0 on development.

The extraction sequence and placing of timber is shown in Figure 0–14. The extraction panel produces on average 33,000 tonnes per month using a remote controlled Joy 12CM12 continuous miner (without the on-board bolting rigs) with three 15 tonne Joy15SC shuttle cars. There is one section miner and six machine operators in this section operating on a two shift per day basis. No use of ABLS's is made although timber is extensively used. The overall extraction, as a result of the implementation of this partial pillar extraction technique, has increased from 35 percent to 45 percent.

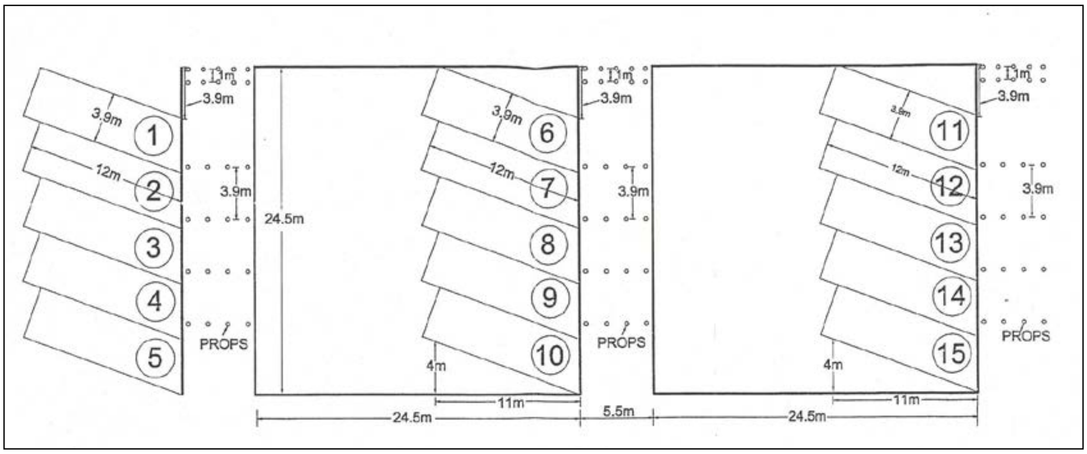


Figure 0–14 Approved partial pillar extraction sequence at Clarence Colliery

The ventilation of the panel is split along the centre of the panel and returned through the two roadways adjacent to the barrier pillars. In this way any dust is moved immediately away from the continuous miner operator through the section before returning along the barrier roads from the rear of the panel.

No adverse effects have thus far been encountered with this extraction technique. It was designed specifically to increase overall extraction while not creating a goaf. Three panels have to date been successfully extracted in this manner. Although previously extracted areas using this method have loaded (by observing the timber props having buckled), it appears as if any further roof movement has consolidated. The area is overlain by state forest and maximum of 12 mm surface subsidence has been noticed. No changes in the coal quality were noticed as the pillars were not old at the time of extraction and they were not subjected to unusually high abutment stresses. The high speed of the operation was expressed as the only concern, with the continuous miner overheating and tripping on numerous occasions as a result. The layout and extraction sequence of this operation are similar to the workings at both Munmorah and Cooranbong Collieries.

Munmorah Colliery

Munmorah Colliery is a 30-year-old bord and pillar mine that conducts secondary extraction. It is situated near the town of Doyalson, which is about 150 km north of Sydney and 30 km south of Newcastle, in the Newcastle coalfield (see Figure 0–1) and it mines the Great Northern coal seam. The mine has employed various total and partial extraction-mining methods throughout its existence. The Great Northern coal seam is overlain by massive conglomerate to sandstone, which is interbedded with mudstones and fossilised bands. However, the mudstone becomes more consistent as a 0.5 m thick continuous layer that overlies the coal seam towards the south-west of the mine and this is cited as a constraint to the mine’s life (which is currently expected to be 2 – 3 more years) as this layer swells when in contact with water and effectively provides no roof contact. As the coal is not washed, this mudstone would also contaminate the product, which is used exclusively by a nearby power station. The floor consists of shales and tuffaceous siltstones and sandstones that are weak and breakdown in some areas. This layer has been the focus of research into the effects of soft floor conditions affecting pillar design (Vasundhara, 1999). The seam in approximately 2.4 m thick and lies approximately 300 m below the surface. The Great Northern seam is the only seam mined at the colliery. The Wallarah seam is 28 - 39 m above the colliery’s workings and is 0.4 - 1.2 m thick. The Chain Valley Seam lies 12 - 15 m below the colliery’s workings and is 1.6 - 10.9 m thick. Neither of these seams has been mined in the lease area, nor is there any future plans to extract them. The area currently being mined (Figure 0–15) underlies medium density housing, vacant land and some commercial and light industries. To undermine these structures, a mining method had to be developed that would limit surface subsidence to a minimum, while maintaining maximum extraction of the reserve and negating the effect of windblasts associated with the previous full extraction techniques at the colliery.

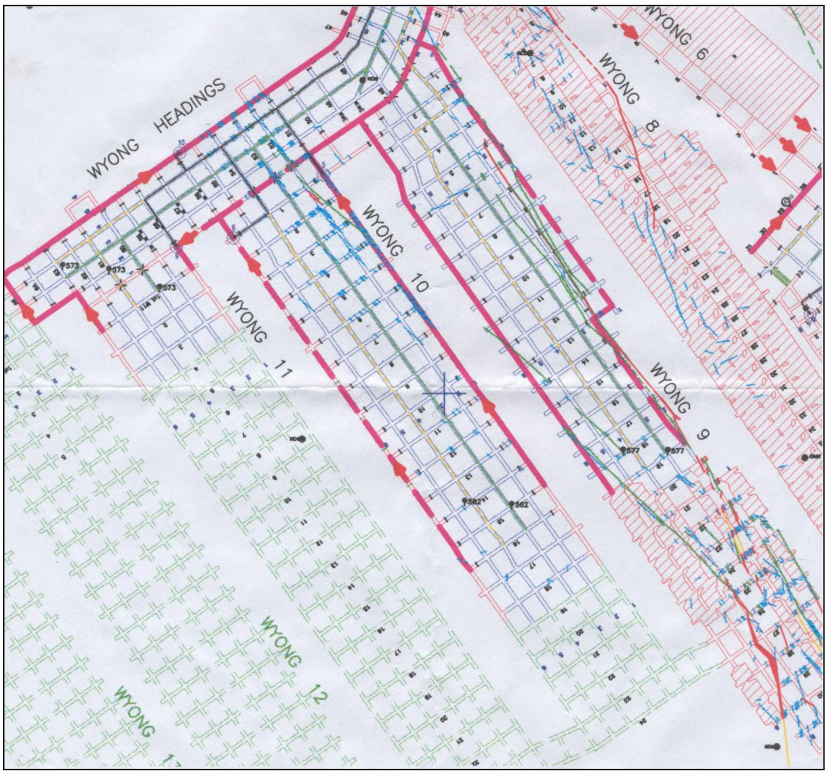


Figure 0–15 Current mining area at Munmorah Colliery

A partial rib stripping extraction-mining method was developed. A six heading panel is developed, separated from adjacent panels by 84 m wide barrier pillars. The centre pillars are larger than the rest of pillars, designed to be 46 m square, while the other pillars are 46 m long by 30 m wide. The panels are developed to the point at which the incumbent areas of mudstone overlying the coal seam (as mentioned before) become an operational hazard. The roads are supported by a twin boom Fletcher roofbolter installing four 1.8 m long full column resin bolts per row with straps, with the rows spaced 2 m apart. A two heading bleeder road used as a return is driven at the back of each panel to the preceding extraction panel which is used to positively free ventilate the active goaves that form during the partial extraction process, to dilute continuously any flammable and noxious gases to safe levels and also to prevent accumulations. A ventilation velocity of 25 m^3 per second is considered sufficient in these extraction panels across the negative differential through the bleeder roads. The development bord and pillar section produces approximately 30,000 tonnes per month (with one section miner, 7 machine operators and 2 artisans) and this is achieved utilising a remote controlled 12CM12 continuous miner and three 15 tonne capacity Joy15SC shuttle cars.

The retreat partial extraction system begins upon completion of the development utilising an open ended lifting approach. The barrier pillars are lifted to a maximum depth of 12 m (making the barrier pillars a nominal thickness of 60 m) and the two pillars on either side of the centre pillars are lifted (with all lifts at an angle of approximately 60°) in a manner shown in Figure 0–16 to create a system of ‘saw toothed’ fenders between the barrier pillars and centre pillars. Single sided lifting takes place when the pillars adjacent to the centre pillar are lifted. The fenders are of sufficient width to height ratio to prevent sudden collapse and may crush as the panel retreats. Spans of 30 m are subsequently created into which the localised goaf will fall (which consists of approximately the first 10 m of the overlying strata). The extraction layout aims to maintain the mining operations within the shadow of support offered by solid coal pillars and the substantial pillars that remain.

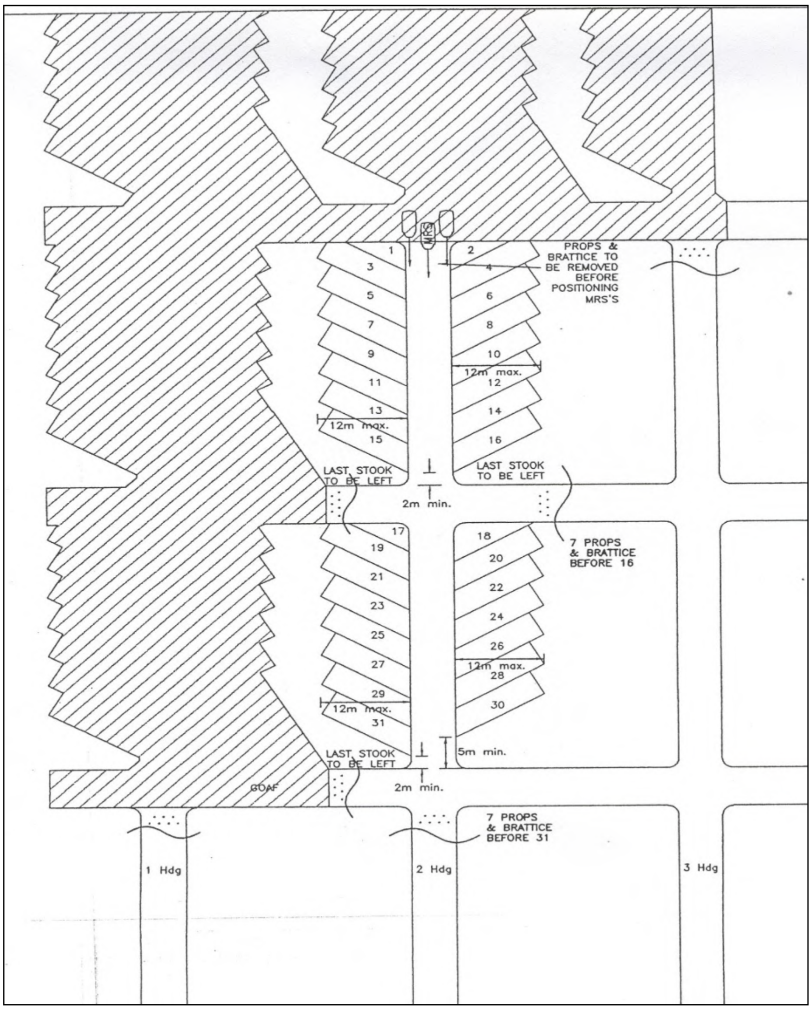


Figure 0–16 Partial extraction layout at Munmorah Colliery

The partial extraction section produces approximately 35,000 tonnes (with one section miner, 4 machine operators and 2 artisans). The extraction system uses a remote controlled Joy 12CM12 continuous miner with three 10 tonne capacity Joy 10SC32 shuttlecars and three remote controlled 600 tonne Voest Alpine Breaker Line Supports (ABLS's) to conduct lifting of the pillars. Only two ABLS's are used when single sided lifting is conducted. The ABLS's are allowed to move forward, one at a time, to a maximum of 4 m before being set to the roof. They are spaced a maximum of 2 m apart with the middle ABLS (when three are used) required to follow the centre line of the roadway.

This method of partial extraction has to date had no adverse effects on surface subsidence, with the overall subsidence being considered minimal (with 20 – 30 mm measured above the current panel). The overall approach has increased the total recovery of reserves to 60 percent, thus leaving 40 percent of the area in the form of pillars and fenders as support. The previous hazards associated with windblasts at the colliery, which are dependant on the strength of the immediate roof (up to 10 m) and its likelihood to cave, have been minimised as a result of the following attributes of this mining method:

Panel geometry to control caving behaviour of the goaf and the size of goaf falls,
Manner and sequence of extraction,
Flood ventilated goaves to remove flammable and noxious gases,
Ventilation and stopping design,
Installation of overpressure device installed at the tail end of the belt that trips the power supply in the even of a windblast occurrence.

The goals of the mining method have all been achieved in that the mining method has not encouraged caving, is safe from the effects of windblasts and has increased the life of the mine through maximising extraction. Further, as the pillars were never more than 2 years old, no changes were noted in the quality of the coal produced from this mining method. Incidences of frictional ignition have been reported before, but the effects of this have been minimised through a well-designed ventilation layout. Further, operating costs were indicated as being less than the development operation by virtue of less labour and less support costs.

Cooranbong Colliery

Cooranbong Colliery is a 1.3 million tonne per year producer of thermal coal, all of which is supplied to a local power station. It is situated in the Great Northern coal seam and is some 20 km north of Munmorah Colliery (see Figure 0–1) and operates in very similar geological conditions to that of Munmorah Colliery. The immediate roof is a massive conglomerate approximately 2 – 3 m thick, interjected by fossilised bands and lenses of sandstone. The floor consists of a 3 m thick pipe clay layer (a natural aquifer) which swells when in contact with water creating problems with floor heave throughout the colliery. The colliery lies within severe geological zones such as a dolerite sill to its east and a large number of fault zones interjecting the entire lease area. The mine is approximately 50 m – 85 m below the surface and underlies residential areas, national railway lines as well as the Dora Creek. The extraction site visited was situated at 50 m below surface.

Various mining methods have been used with success at Cooranbong Colliery in its 20-year history. Initially, bord and pillar mining was conducted with secondary extraction before 8 longwall panels were successfully employed in the northern area of the mine in the mid-1980's. However, the mining height fell below the design parameters of the longwall equipment of 2.7 m and, as no washing of the product is conducted to remove impurities, an alternative mining method had to be designed to maximise extraction of the remaining reserves situated at a height of approximately 2.5 m. The current rib stripping method of partial extraction was thus designed to also combat goafing of the area.

The mining method requires the driving of seven roadways, creating pillars 40 m by 30 m with a bord width of 5.5 m. Upon completion of this development, the pillars are partially extracted by right and left lifting of the rib sides in a manner shown in Figure 0–17 by lifting 10 m of each of the ribs on the smaller axis to create pillars that are nominally 20 m by 30 m.

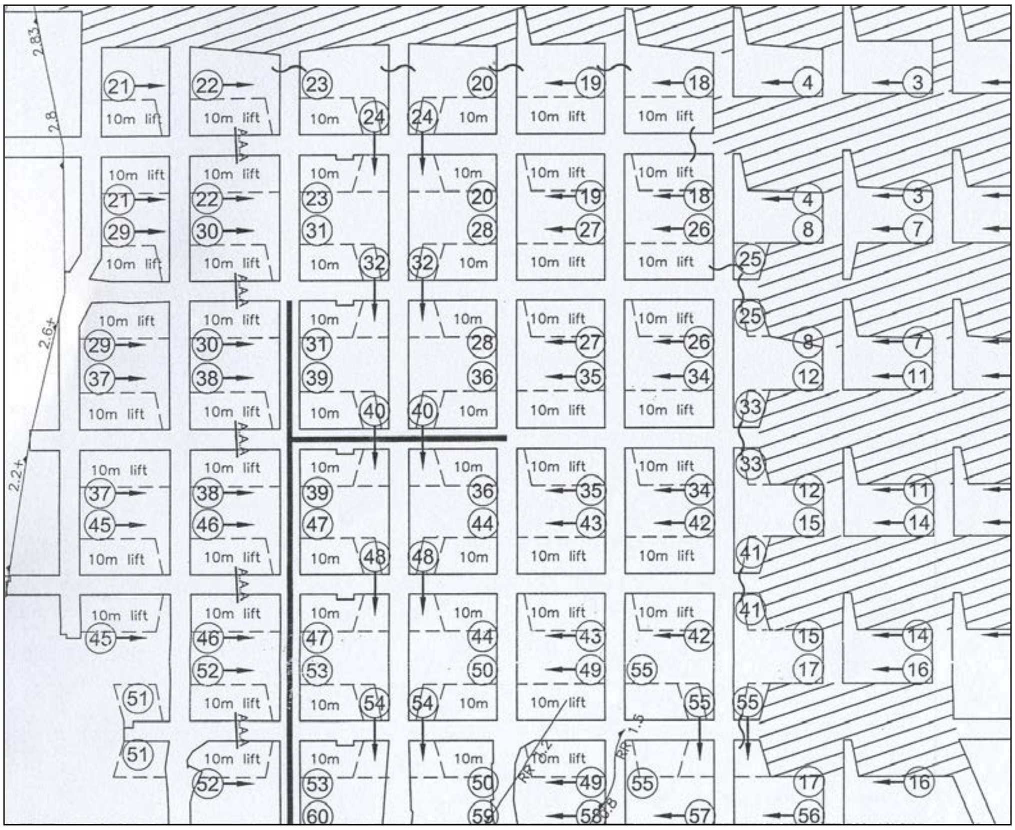


Figure 0–17 Partial extraction layout at Cooranbong Colliery

There were two development sections and one extraction section operating at the time of the visit. All the sections operate a remote controlled Joy 12CM12 continuous miner and two Joy 15SC shuttle cars with the extraction section utilising three remote controlled 600 tonne capacity Voest Alpine Breaker Line Supports (ABLS's). The ABLS's are moved one at a time to a maximum of 2 m and spaced a maximum of 2 m from one another. Where three ABLS's are used, the middle ABLS follows the centre line of the roadway. On development a Fletcher type roofbolter is used to install 2 full column resin spot bolts per row, spaced 1.5 m apart, in good conditions. In poorer roof conditions a combination of 4 full column resin roofbolts with straps or meshing are used. As the conglomerate roof is generally uneven, a scaling machine is used prior to roofbolting to clear the roof of any lenses of coal that pose a roof fall hazard. The pillar extraction operation with the use of ABLS's is shown in Figure 0–18.

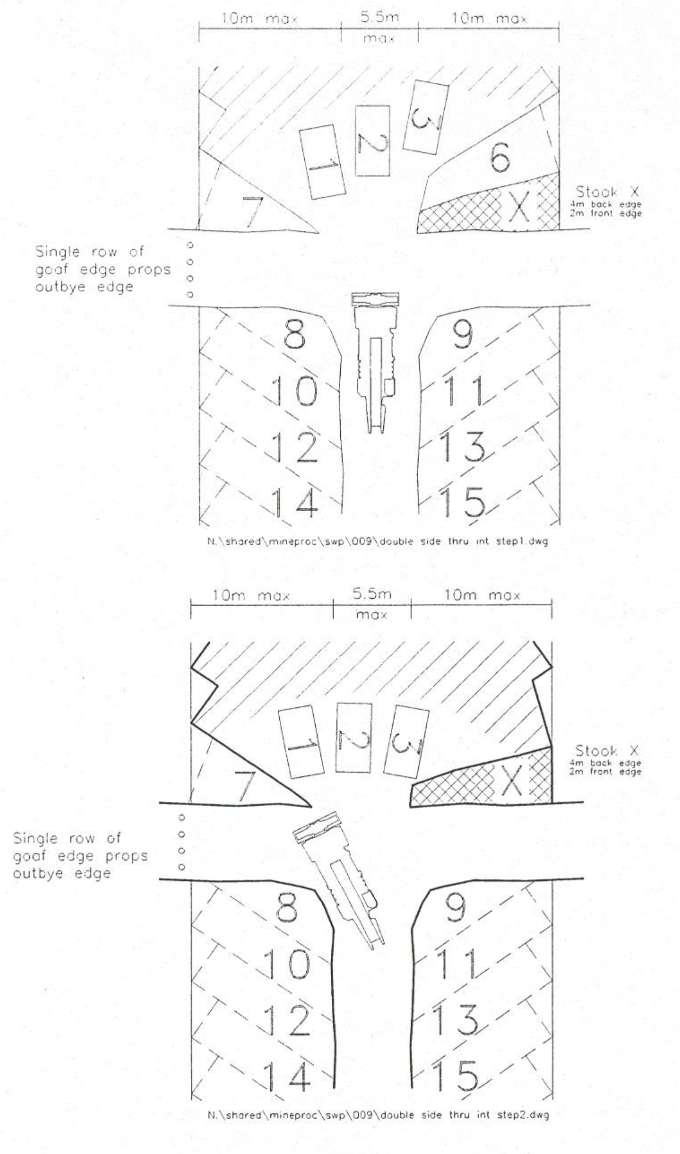


Figure 0–18 Use of ABLS's during partial extraction at Coornabong Colliery

In addition to the ABLS support, a row of timber breaker props is set on the outbye goaf edge (as shown in Figure 0–18). This extraction operation yields a production of approximately 750 tonnes per shift on 14 shifts per week, with one section miner and 5 machine operators per section per shift. The two development sections produce 550 tonnes per shift each with 19 shifts per week. Each of the development sections has one section miner and 7 machine operators.

Goafing is localised in its nature and is limited to small areas where sandstone lenses are found. Although post extraction a span of approximately 26 m is created, the massive conglomerate roof is capable of spanning the distance successfully and eliminates the risk of a goaf. No adverse effects have been experienced with this mining method, although methane build-up and its associated frictional ignition hazard is a major safety factor which is negated by forcing ventilation through the mined out area at 25 m^3 per second. The pillars were extracted upon completion of development resulting in no variation in the yield as no ageing effects were noticed. No surface subsidence was expected and current measurements have shown little to no effect on the surface as a result of this mining method.

Review of full pillar extraction operations in New South Wales

Four full pillar extraction operations in New South Wales were visited while some information was obtained from a fifth operation that has recently ceased this mining practice. Of the four operations visited, one was in the Southern Coalfield, two in the Western Coalfield and one in the Hunter Coalfield. All operated under vastly different circumstances and conducted this mining practice for a variety of reasons. The pertinent factors relating to each of these operations is discussed here.

Review of pillar extraction at Bellambi West Colliery

Bellambi West Colliery operated under unique circumstances in that chain pillars that previously acted as barrier pillars and main travelling ways between two longwall goaves were extracted. A modified Wongawilli method was the most suited under the given circumstances. In terms of this interaction of goaves coupled with the depth of the operation, the focus in its design came in successfully creating a goaf while creating snooks and fenders large enough to maintain a safe working environment. The extraction panels were both long and narrow (2,500 m long and 195 m wide). This panel geometry (when designed in virgin ground) would generally limit full caving and limit abutment stresses. The panel width to depth below surface (W:D) was 0.46. Generally, for New South Wales conditions, when the W:D ratio is greater than 1.4, full caving can be expected and when the ratio is greater than or equal to 2 one can expect surface disturbances. These guidelines however exist for planning extraction panels in virgin ground and in this case would not necessarily apply, as the surrounding conditions of the previously created goaf dictated the nature of the caving. Effectively, these panels acted as a pivot separating previous goaves and extracting them merely encouraged caving and in so doing consolidated the existing goaves. As a result, early caving closely followed the extraction line. The subsidence resulting from the operation would also be an extension of the subsidence already caused by the previous longwall operations.

The extraction at Bellambi West Colliery was an opportunistic decision to maximise the recovery of reserves to extend the life of the mine. The use of remote controlled continuous miners and ABLS’s ensured its general success. One of the most important design features of this extraction method was the leaving of snooks around intersections approximately 12 m^2 in area (see Figure 0–

3). This translates into the snook having a carrying capacity of 5,500 tonnes. Once a sufficient area around the snook has been extracted, it will fail under the deadweight load of being 420 m below surface. The ancillary support from the timber props and the ABLS's have significantly lower carrying capacities and serve merely to provide an additional safety zone under which the continuous miner operator can work, while also controlling the overlying strata and breaking off the goaf in a controlled fashion.

The change in the extraction sequence (as shown in Figure 0–2 and Figure 0–4) indicated that the layout shown in Figure 0–4 created a situation whereby caving could not be induced readily in that the extraction layout was irregular. The change to the more structured layout in Figure 0–2 ensured that extraction occurred in a straight line and thus created a goaf readily in the same straight line.

Review of pillar extraction at Charbon Colliery

Charbon Colliery operated in unique conditions in terms of the depth below surface being variable at all times, leading to a continuous dynamic stress regime dependant on location under the mountainous overburden. The depth below surface of the panel visited varied from 30 m at its most outbye position, 190 m at the centre and 150 m at its most inbye position.

The modified Wongawilli extraction technique required that the solid side of the panel is developed regularly with all splits and run outs fully driven before the retreat extraction begins, as opposed to the goaf side of the panel where the splits and run outs are created and supported only once the panel has started retreating. Effectively the panel is thus only half developed before the retreat operation commences. This practice is done to limit the creation of 4-way intersections, which had in previous instances required expensive cable truss supports as a result of poor geological conditions. The practice of creating pillars at the last possible moment thus also limited the interaction of the stresses associated with the previous goaf and minimised the effects of time on the pillars, as the average age before extraction of these pillars created nearest the previous goaved panel was one week. Snooks were left in every pillar extracted as depicted in Figure 0–6. Each of these triangular snooks has an approximate load bearing capacity of 20,000 tonnes (with an area of 25 m^2) while the larger snooks left on the solid side of the pillar (50 m^2) are in excess of 50,000 tonnes. As mentioned previously, these larger snooks are left to control return ventilation and are virtually indestructible in terms of their location and load bearing capacity. The smaller snooks created on the goaf side of the panel together with the larger snooks of the previous panel provide support to a 25 m by 20 m area which ensures the area doesn't collapse and in so doing ensuring that the return ventilation airway remains open. The smaller 25 m^2 snooks in the centre of the panel are weak enough to collapse when the 30 m wide created span collapses. Each panel creates a new goaf and the nature of the weak roof ensures that goafing closely follows the extraction line. The nature of the dynamic roof loading conditions, together with the dynamic panel creation and extraction, make it difficult to quantify the exact nature of the operation, suffice to say that the extraction operation under these conditions was very successful. Again, the use of timber props and ABLS's ensures a safer working environment.

Review of pillar extraction at Ivanhoe Colliery

The full extraction operation at Ivanhoe Colliery is a good example of maximising extraction of a reserve by extracting existing pillars created by drill and blast methods almost a century ago. The original design parameters of the area being extracted created pillars of width to height ratio equal to 10, and the subsequent brushing of the roadways to the full seam height reduced this ratio to 5.6 before extraction commenced. The overall panel width to depth below surface ratio of 6 indicates that full caving will develop and that surface subsidence will occur (in terms of New South Wales conditions).

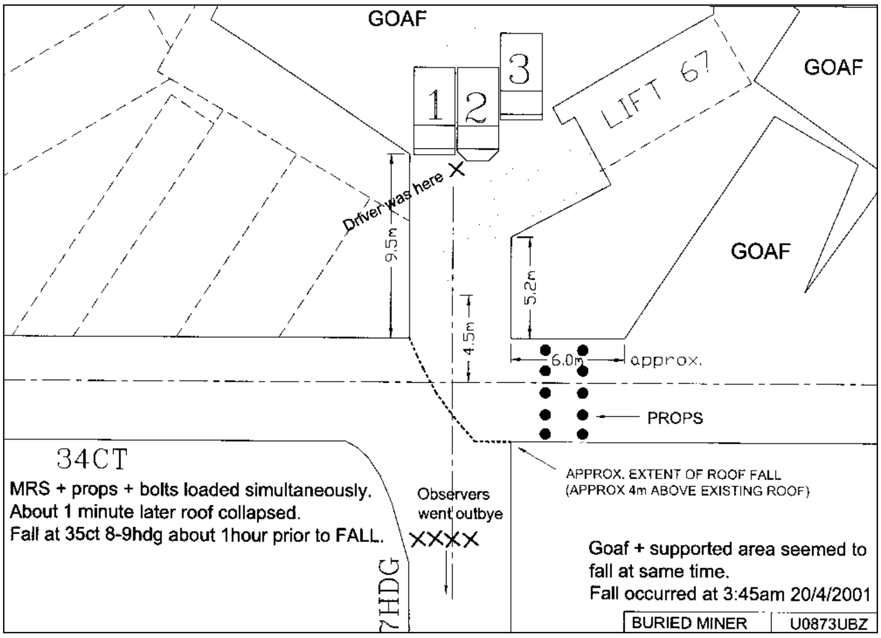
As only single sided lifting is conducted, the approach of leaving snooks is also different from the double-sided lifting operations. Generally at Ivanhoe Colliery, snooks are left where there are geological anomalies (stringers, faults, etc.) or where the direction of mining changes. Rather, a thin fender (approximately 1 m wide) is left at the rear of the pillar being extracted as an additional support. As it is a thin fender it fails readily under the weight from the roof, thus ensuring that the goaf line closely follows the extraction process.

Severe rib crush in an area of the panel (resulting from high abutment stresses) resulted in a small area having to be abandoned. This was a result of the panel being mined out of sequence to mine an irregular shaped area (marked A on Figure 0–8) which resulted in the pillars at the edge of the panel being surrounded by goaf on three sides and creating unusual stress regimes in this area. A further consequence of this area being abandoned is that full caving of adjacent areas was retarded and resulted in further abutment stress problems for subsequent extraction. In general the extraction operated under stress as was observed by the rib spall around pillars adjacent to those being extracted. It is inferred that the age of the pillars are a contributing factor for this, although other factors such as depth below surface, extraction method, etc. would also have contributed to this.

Review of pillar extraction at United Colliery

United Colliery has had the benefit of conducting full pillar extraction using a variety of techniques. The use of the continuous haulage unit obtained variable results with component failure being the major reason for it being discontinued. The nature of the deposit at United Colliery also played an important role in the overall decision to discard the use of pillar extraction in favour of longwall mining. The seam dips in the northeast to southwest direction, which is roughly normal to the number of parallel fault zones, which intersect the entire lease area. The layouts for the extraction panels lie at approximately 45° to the fault planes, which is common mining practice in New South Wales. However, the added problem of the seam dip has resulted in the panel layouts dipping down from right to left when a cross-section of the panel is viewed. In the initial, shallower panels this was not significant, but in the later, deeper panels it required leaving the centre pillars so as to reduce the overall span of the panel and in so doing combat severe rib spall and pillar crush which was more dominant on the pillars on the left hand side (down dip side) of the panel. Figure 0–10 shows that a greater proportion of pillars are extracted on the right hand side of the panel, whereas the pillars on the left hand side were only partially extracted in an attempt to reduce the effects of the high stresses encountered there. The panel being extracted also lies between two previously extracted panels, which have resulted in further high abutment stresses affecting pillar loading in the extraction panel. It was not uncommon for the pillars to be only partially extracted in an effort to combat the negative regimes, but this then lead to the panel being a combination of full and partial extraction which is generally not considered good practice.

The ratio of the width of the panel to its depth below surface of 1.32 indicates that in terms of New South Wales averages that generally full caving will not occur as this is below 1.4. This creates a situation whereby caving may or may not occur. Burial of equipment has also occurred regularly as a consequence of the stresses. Figure 0–19 shows the nature of the most recent equipment burial. The incident occurred while cutting the last lift and being surrounded by goaf on three sides.



MRS + props + bolts loaded simultaneously.
About 1 minute later roof collapsed.
Fall at 35ct 8-9hdg about 1hour prior to FALL.

APPROX. EXTENT OF ROOF FALL
(APPROX 4m ABOVE EXISTING ROOF)

Goaf + supported area seemed to fall at same time.
Fall occurred at 3:45am 20/4/2001

Figure 0–19 Burial of equipment at United Colliery

In general, no regular sizes of snooks or fenders have been left as conditions are dynamic and change from location to location. The decision to replace pillar extraction with longwalling is a combination of the factors as detailed here, with safety being the major factor behind this decision.

Review of pillar extraction at Chain Valley Colliery

As the Chain Valley Operation was not visited and only limited information could be obtained pertaining to the extraction method, no analyses or comments can be drawn. Thus, no further comments regarding the operation can be made.

Review of partial pillar extraction operations in New South Wales

Review of pillar extraction at Clarence Colliery

The partial extraction technique developed for Clarence Colliery required an increase in overall extraction without caving and in so doing limiting the influx of water associated with two overlying aquifers, as well as the problems associated with goafing of the overlying massive Triassic sandstones. The initial panel design of the width of the panel to depth below surface of 0.84 indicates that overall extraction will not induce caving or have surface effects if full extraction is to be considered. Since only partial extraction is used at Clarence, this ratio becomes less important than when considered with full extraction operations. The partial extraction method used here effectively creates two smaller panels within the original panel, separated from one another by the unmined centre pillars. Once partially extracted, the resulting pillars of 24.5 m by 13.5m are large enough to aid the massive sandstone roof to span the resultant 16.5 m bord widths. These pillars have load-bearing capacities of 550,000 tonnes and are considered to be substantial permanent support. The two lines of centre pillars that are left unmined take the most pressure as a result of being larger in geometry than the smaller, partially extracted pillars in the panel. The success of this method has been hampered only by the high rates of extraction achieved and future modifications to this method will include leaving only one line of centre pillars to further increase recovery. No use of ABLS's was made at Clarence Colliery, although a large amount of timber was used in the form of breaker lines. This method has increased the overall extraction by 10 percent to 45 percent.

Review of pillar extraction at Munmorah Colliery

The partial stripping operation at Munmorah Colliery is different from the other partial extraction operations in that the centre line of pillars (which remain as a permanent support) is specifically designed to be larger than the pillars that will be extracted. This would imply that these pillars will take more load from the outset as a result of their larger geometries. The partial extraction of the two lines of pillars on either side of the centre pillars results in the creation of saw-toothed fenders approximately 40 m long and 6 m wide. These fenders have a load bearing potential of approximately 240,000 tonnes. To date there has been no failure of these fenders and they are thus strong enough in aiding the massive conglomerate roof to span the voids created. Also, no negative effect to the soft floor has to date been noticed. The original panel design width to depth below surface ratio of 0.61 is well below the 1.4 required by full caving operations, indicating that this design is suitable for partial extraction. Further, the positive flood ventilation used has successfully ensured that previous problems associated with methane and the risk of frictional ignitions have been minimised. The partial extraction method has also limited the occurrences of windblasts as the massive conglomerate roof is not broken or caved. It has also increased the overall recovery from 25 percent to over 80 percent.

Review of pillar extraction at Cooranbong Colliery

The geological situation at Cooranbong Colliery is similar to that experienced at Munmorah Colliery with the same soft floor conditions and massive conglomerate roof. The partial extraction technique reduces the 40 m by 30 m pillars to 20 m by 30 m, thus ensuring that these provide an adequate permanent support of almost 1 million tonnes each. The maximum void created by this method (25.5 m) is adequately spanned by the massive conglomerate roof. The effects of time have however resulted in the pillars punching into the soft floor and creating floor heave although this does not affect the mining method or surface subsidence. The original panel ratio of width to depth below surface of 4.37 would indicate that full caving and surface interaction would occur if full extraction were conducted. However, the partial extraction technique creates substantial fenders that are designed not to fail. This mining method has increased overall extraction from 25 percent to approximately 75 percent.