

DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

.....

(Signature of candidate)

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ABSTRACT

The majority of bord and pillar coal mines world over utilizes uniform pillars across a panel for ease of layout and simplified standard mining sequence. This is however, regardless of the fact that the distribution of vertical stress across all the pillars from barrier pillar towards the centre of the panel is not uniform.

The distribution of vertical stress, safety factor and seam convergence across panels at various depths have been investigated through the Lamodel software package. Further verification of the distribution of stress has been done through underground investigations on the effects of stress on pillar scaling in a main development panel of a bord and pillar coal mine. Both numerical and underground investigations have confirmed that in-panel pillars close to barrier pillars have higher safety factors than those in the middle of a panel.

Based on this, further numerical modelling using the Lamodel package has been conducted focusing on the size and location effects of barrier and in-panel pillars in bord and pillar panels at different depths. It has been found that it may be possible to improve coal resource utilization without significantly affecting stability by slightly reducing the size of those pillars close to barrier pillars, changing sizes of pillars in the middle of the panel and considering barrier pillar partial extraction.

Based upon the indicators identified in the models investigated, a panel's overall extraction in bord and pillar primary development may be increased by between 0.01% and 0.88% depending on depth and layout configurations.

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LIST OF SYMBOLS

ALPS – Analysis of Longwall Pillar Stability

ARMPS – Analysis of Retreat Mining Pillar Stability

B – Bord width

BP – Barrier Pillar

e – Areal extraction (%)

e_o – Overall areal extraction taking into account the width of barrier pillars

H – Depth of workings

h – Mining height

m – Seam thickness

MULSIM/NL – A boundary element programme developed by NIOSH that uses a post failure stability criterion in mine design

n – Number of bords / roadways

P1 – In-panel pillars adjacent to barrier pillars

P2 – In-panel pillars adjacent to P1 pillars

P3 – Pillars at the centre of the panel

SF – Factor of Safety

v – Volumetric extraction

VSF – Vertical Stress factor, the ratio of vertical stress to depth

W – Pillar width

NOMENCLATURE

Barrier Pillars – Any large block entirely or relatively unbroken by mining development left unmined to protect adjacent mine areas from adverse effects of vertical stress and water.

Bord - An opening formed by mining using the bord and pillar method of mining. Bords are areas from which the coal has been mined; pillars are the areas of coal left between the bords.

Bord and Pillar – A mining method which extracts the coal in the bords (openings) and leaves pillars (unmined blocks of coal) to support the overburden.

CM – Continuous Miner, coal cutting machine used in mechanized bord and pillar mining.

Convergence – The vertical closure of an opening as a result of movement from the top, the bottom or both top and bottom.

Crosscut – An opening driven between two entries for the purpose of ventilation and haulage.

Element – The volume of material assigned the same material properties. Each element consists of an assigned length and width (size) and a corresponding thickness (coal height). The properties of each element are used in the calculations performed within a boundary-element analysis.

Entry – An opening driven in the coal to advance a mining area. Entries may be used for personnel and material haulage and ventilation requirements.

LaModel - A pc based, three dimensional boundary element program for calculating stresses and displacements in coal mines or other mines extracting thin, tabular seams or veins.

Lamplt - The post-processor that allows the user to plot and analyze the output from Lamodel.

Lampre - The pre-processor that facilitates creating the input file for Lamodel which then calculates the stresses and displacements at the seam level from the input.

Overburden – The rock and soil above a coal seam.

Pillar – The block of material left in place usually to provide support.

Pillar Strain Safety Factor (PSF) – a measure of pillar stability relative to the deformation (strain).

Roof – The rock above the top of a coal seam, typically sandstone or shale.

Roof bolt – A long steel bolt inserted into walls or roof of underground excavations to strengthen the rock strata.

Safety Factor (SF) – A measure of pillar stability relative to the vertical stress or the deformation (strain). A higher resulting number indicates more stability.

Strain – Change in shape or volume of a body as a result of stress; deformation resulting from applied force.

Stress – The force per unit area acting on any solid surface, generally expressed in mega pascals (MPa).

TAT – Tributary area theory used in determining the loads on pillars in bord and pillar panels.

Vertical Stress – The downward stress exerted on an object (pillar) created by the weight of material from the ground surface down to the object.

Yield – The pillar action resulting in gradual crushing of the pillar ribs resulting in convergence.

Yield Pillar – A pillar designed to gradually crumble reducing the potential to develop or carry significant vertical stress loads. Peak vertical loads are transferred to adjacent larger pillars or barriers.

CHAPTER 1

Introduction

1.1 Background Information

Bord-and-pillar geometries are laid out in a compartmentalized form consisting of in-panel pillars and roadways, with individual working panels being separated by barrier pillars. If the strength of a pillar in the set-up is exceeded, it will fail, and the load that it carried will be transferred to neighbouring pillars, which may lead to a rapid pillar collapse of a mine (Zipf, 2001). An extensive pillar collapse can be controlled by barrier pillars. Thus, both in-panel and barrier pillars are important components making up a bord-and-pillar panel layout. Their sizes should be neither too small to support roof loading nor too large to reduce productivity. An understanding of the size relationship between them, along with the size of the panel and other important factors that govern stability is essential for optimization of extraction under stable conditions.

In panel pillar designs, the size of pillars is determined by the requirement that the roof should be adequately supported (Salamon, 1967). The general design consists of determining the maximum depth of the panel, mining height, bord width and pillar dimensions (Van der Merwe and Madden, 2002). A number of pillar design formulae have been developed around the world (Mark, 2006) and are generally based on the estimation of the pillar load using the tributary area theory, estimating pillar strength using a pillar strength formula and calculating a factor of safety. Notable among these formulae and with a wide application in the South African coal mining industry is the

Salamon and Munro formula (1967) for estimation of pillar strength as well as its extension, the squat formula.

As with in-panel pillars, there are also several design formulae for barrier pillars, all of them empirical (Peng, 1986). In the formulae, the width of the barrier pillars is generally a function of the overburden height. Salamon (1967) mentions that, in the design of barrier pillars no consideration of pillar strength is involved in determining the dimensions of these pillars, but attention is given to the stresses and displacements, induced by mining, in the vicinity of the structure for which protection is intended. Later on it was realised that based on strength considerations alone, barrier pillar width depends on panel width (Zipf, 2001); a narrow panel will require a narrow barrier pillar and a wide panel will require a wide barrier pillar. In this case a relationship is thought to exist between the width of the panel and that of the barrier pillars; the width of the in-panel pillars is however ignored.

The guidelines for designing barrier pillars in South Africa were introduced by Esterhuizen (1992) who suggested that the barrier pillar width should be at least equal to the in-panel pillar width in order to arrest collapse. Consequently, barrier pillars on most collieries (Rangasamy, et al, 2001) were reported to be related to the width of the pillars in the adjacent workings. Effectively, a relationship between the width of the barrier pillar and that of in-panel pillars has been established, though however not directly linked to panel size and stability.

The tributary area method applied in the traditional strength-based design methods only provides a first-order estimate of average pillar stress (Zipf, 2001) and makes many simplifying assumptions and cannot be relied upon entirely. It has also been recognised that in narrow panels the pillars near the edges might not experience the full load (Mark, 2006). If this is the case, potential therefore exists to increase extraction through reducing the size of in-panel pillars next to barrier pillars with the panel remaining stable.

The effect of the size of the barrier pillars on overall extraction has been indirectly illustrated by Salamon and Oravec (1976). Overall extraction is indicated as a function of both barrier pillar and in-panel width. Increasing both of them reduces extraction and a reduction in their widths will impact negatively on stability. Thus, it may be possible to increase extraction through reducing the in-panel pillar widths for an increased barrier pillar width. This however has to be linked with the stability of the panel.

A further understanding of pillar mechanics came with the development of computer models that can accurately predict pillar behaviour (Mark, 2006). Loui and Sherry (2001) outlined a method of estimating the maximum width of a panel for different shapes in room and pillar extraction, focusing mainly on avoiding subsidence, using elastic analysis. Adhikary et al (2002) carried out numerical work to investigate the stability of a highwall mining panel using the local mine stiffness theory. Using the same theory Zipf (2001) described an evaluation of a factor of stability that may enable safe bord and pillar mining. His work, together with those of many others, concentrates on preventing massive pillar collapses in bord-and-pillar workings.

Thus, little attention has been given by both empirical and numerical methods to the influence of barrier pillars on the stability of in-panel pillars. An understanding of the stability behaviour of both types of pillars is essential when considering optimized extraction that does not compromise the stability of workings.

1.2 Problem Definition

While coal pillar design since the Coalbrook disaster is quite successful and the purpose of barrier pillars in containing a collapse is generally recognized, the extent to which the barrier pillars affect the stability of panels through their relationship with in-panel pillars is often not appreciated. If the size of barrier pillars has an effect on

the stability of in-panel pillars, then extraction can possibly be improved by reducing the sizes of the in-panel pillars and increasing that of barrier pillars. Stability also needs consideration, so that the safety of men and equipment remain uncompromised with increased extraction.

A good understanding of the influence of the barrier pillars on the stability of in-panel pillars in coal bord-and-pillar panels is essential, so that layout designs can consider an improved overall extraction whilst maintaining panel stability.

1.3 Objectives

This project aims at determining optimized bord and pillar geometries that consider the influence of barrier pillars on the stability of in-panel pillars. The project will demonstrate a number of ways in which the unequal distribution of vertical stress across panels can be utilized in improving extraction without significantly affecting the overall stability of panels.

1.4 Methodology

A review of both in-panel and barrier pillar design mechanics for bord-and-pillar mining has been undertaken. For a more practical approach, underground investigations at some coal mines employing the same extraction technique have been carried out. Combining theory and practice, a systematic approach has been taken with the aid of numerical modelling techniques to determine safe and optimum coal extraction through varying the sizes of the in-panel and barrier pillars.

1.5 Content of Dissertation

Chapter 2 gives a literature review pertaining to the empirical design of in-panel and barrier pillars in coal mine bord and pillar workings. Chapter 3 introduces numerical modeling as applied in coal pillar designs and gives an initial investigation into the effects of varying barrier and in-panel sizes on panel stability and extraction using the Lamodel numerical modeling software package. An underground investigation to establish the effect of vertical stress on pillar scaling across a development panel in a bord and pillar mine is covered in Chapter 4. Based on the findings of Chapters 3 and 4 coupled with the literature review, Chapter 5 analyzes and discusses alternative optimized bord and pillar layouts that take into account the effect of both barrier and in-panel pillar size and location. The conclusions and recommendations from this research are given in Chapter 6.

CHAPTER 2

Literature Review

2.1 Introduction

Bord-and-Pillar mining offers great operational flexibility, relative freedom in the sequence of extraction, insensitivity to local and regional geological disturbances, maintenance of the integrity of the roof strata and surface, and low capital intensity (Wagner, 1980 and Singh, 1997). It is due to these advantages that it is still the most important method of underground coal extraction in South Africa, accounting for more than half of total production (Ndlovu, 2006 and Chamber of Mines of South Africa, 2007). However, the main disadvantage of the method is that coal has to be left in situ to support the roof strata. Accordingly, the pillar has always been the most critical structure for successful coal mining operations and its design remains significant in South African mining (Madden et al, 1998).

This chapter critically reviews the empirical design of bord and pillar workings through focusing on the main elements of the system, i.e. the panel, in-panel pillar size, the size of barrier pillars as well as the size of the bords. Attention is also given to roof support mechanisms in bord and pillar workings as well as production considerations through investigating the effect of various parameters on factor of safety and extraction.

2.2 Bord and Pillar Method Description and Application Environment

Bord and pillar is a low cost and low capital input method that is particularly suited to shallow and thick seams with a horizontal or flat dip (Singh, 1997). The method consists of an initial series of entries that are driven either from the mine portal or from the shaft bottom to intersect the seam/s. As the entries are driven into the seam, crosscuts are developed between them at regular intervals, leaving in-panel pillars. A typical layout of bord and pillar workings is shown in figure 2.1 below. From the main entries, multiple panel entries are developed at regular intervals leaving barrier pillars between the panels.

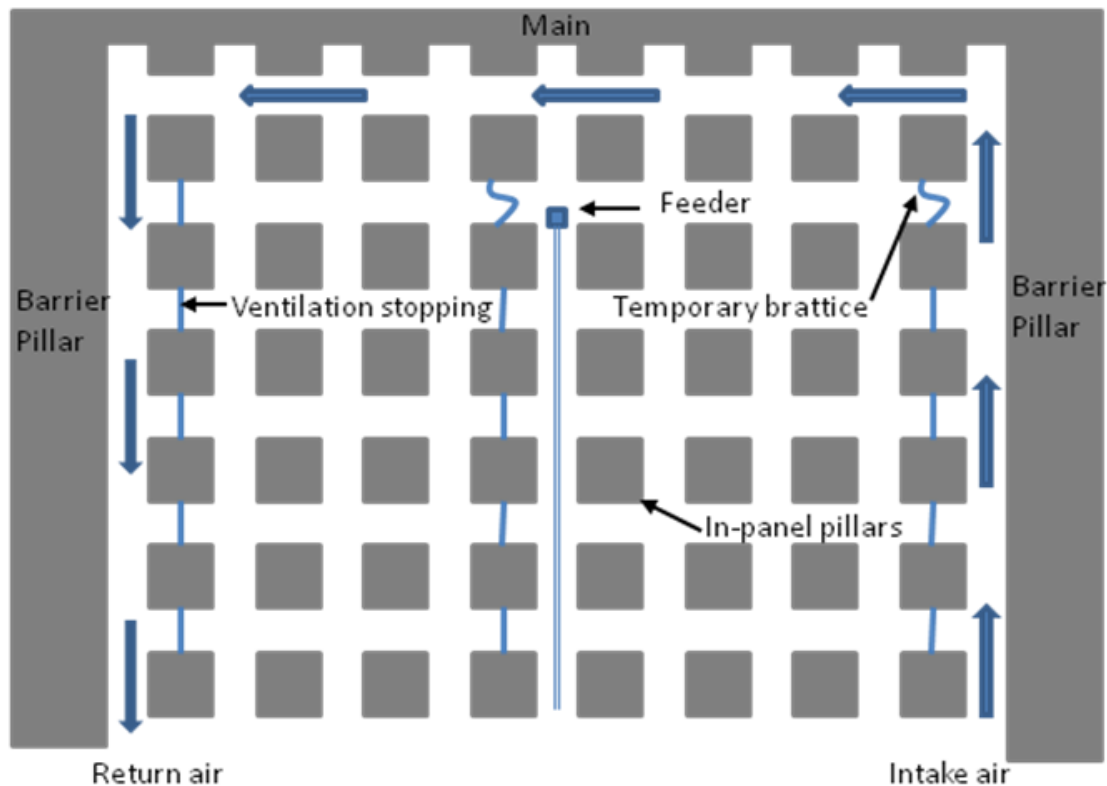


Figure 2.1: A layout of bord and pillar workings (Brumby, 1980)

The number of development headings depends on the following factors (University of Wollongong, 2008):

- Mine capacity,
- Pillar and or pillar and panel system relating to depth of working, productivity and panel extraction system,
- Number of continuous miner units operating,
- Coal clearance system,
- Men and material transport, and
- Ventilation.

The dimensions of the bords and pillars depend on the stability of the roof and the coal itself, thickness of the deposit and the rock pressure (Hamrin, 1980). Depending on the size of the bords and the pillars, the amount of coal removed from production areas commonly ranges from 40% to 70% (Illinois Department of Natural Resources, 2008).

2.3 Empirical Pillar Design Methodology

The empirical pillar design formulae (obtained from field observation) rely on a scientific interpretation of actual mining experience. The methods, whose large database came from bord and pillar mining, have been widely accepted in the coal mining industry (Gale, 1999 and Van der Merwe, 2001) particularly in bord and pillar mining under relatively shallow cover. They basically consist of three steps (Mark, 2006) discussed in detail in section 2.5:

- a) Estimation of pillar load (using the tributary area concept).
- b) Estimation of pillar strength as a function of the width to height ratio and coal strength.

- c) Evaluation of the pillar stability through the determination of the safety factor.

Pillar dimensions are chosen so that the pillar load, when increased by a reasonable margin of safety, is equal to the pillar strength. Essentially, empirical approaches facilitate the derivation of a probability of success in a particular situation, based on the analysis of prior successes and failures (Hill, 2005).

The methods have the advantages of being close to reality and easy to use. However the design formulae have been developed on a probabilistic basis, and they need to be reviewed periodically as the database expands. They also provide little direct insight into pillar mechanics – inherently ignoring roof and floor end constraint and subsequent interactions as well as pre-mining horizontal stress and possible shear load (Daniel and Hasefus, 1999).

These shortcomings have led to the development and application of numerical methods in coal pillar design (Chapter 3).

2.4 Panel Layout Design

One of the considerations in deciding the size of the panel, is the rate at which extraction is done (Singh, 1997). With high rates of extraction made possible by mechanization, the size of the panel can be significantly increased. Rangasamy, et al (2001), mention that mining panels are positioned according to:

- Mine boundaries: previous mining areas,
- Legislative constraints,
- Quality of coal,
- Geological and rock-engineering constraints: floor, roof and seam thickness contours, sills, dykes, burnt coal and hydrological areas,

- Life of mine strategy and production needs, and
- Ventilation needs

An example of application of rock-engineering or strata control considerations in determining panel sizes is in the ‘yield pillar’ technique in which the panel size is fixed so as to cause the main abutment pressure to be carried by barriers, which are of substantial width, and the pillars in the panel are made smaller so as to ‘yield’ and throw the limbs of the main pressure arch (Section 2.5.1b) on barriers. This way the percentage extraction from a panel can be substantially increased (Singh, 1997).

According to Chase and Heasley (2001), one of the strategies employed in coal mines is to develop a wide section (9 or more entries) the entire length of the panel advance, and then recover the pillars on retreat. In this approach, large production pillars are developed with the intent that they, and the adjacent barrier pillar(s), should be able to withstand all anticipated loading conditions encountered during advance and on retreat. This however requires pillars that are too wide at greater depths. Another approach is to advance a narrow panel (4 or 5 entries), leaving a large barrier between the section and the previous panel gob. On retreat, rooms are driven into the barrier and then these and the panel production pillars are recovered all the way across the section. The advantage of this technique is that, if problems are encountered on retreat, development into the barrier can be halted and a few rows of production pillars can be left intact so as to contain or isolate the problems inby.

Latilla (2003), in investigating the influence of weak floors on pillar stability, suggested that panel widths should not exceed 150m with the continuous inter-panel barrier pillars at least as wide as the pillars in the adjacent panel. Where the pillars in two adjacent panels are of differing sizes, he further suggests that the inter-panel barrier pillar must be the width of the wider of the two pillar sizes.

2.5 In-Panel Pillar Design

In-panel pillars are interior pillars which are designed to support a mining panel (Ryder and Jager, 2002). There are basically, three types of in-panel pillars that can be found in bord and pillar mining, defined according to Nzenga (1998) and Wagner (1980) as follows:

- **Non-yield (elastic) pillars** - these are pillars that are supposed to remain intact and elastic during the life of the mine. This assumes that the strength of the pillar should be higher than the average stress due to the weight of overlying rock.
- **Yield Pillars** - These are pillars designed to be initially intact, but can yield in a stable manner when loaded beyond their peak strength as mining progresses.
- **Slender / Crush Pillars** - These are pillars with a small w/h ratio designed to crush while they are either still part of the face or in the back area at shallow mining depth. Their post peak residual strength provides sufficient support resistance to the immediate hanging wall.

The dimensions of these pillars will be largely determined by what is expected of them and the period of time for which they must remain stable.

2.5.1 Estimation of pillar load

There are two methods that explain preliminary pillar loading, the tributary area method and the pressure arch theory.

(a) The tributary area method

The Tributary Area Method (Farmer, 1992), provides a first order of average pillar stress. According to this concept, a pillar takes the weight of overlying rock up to a distance of half the opening width surrounding it (Figure 2.2). The following assumptions are made:

- The mined area must be extensive,
- All pillars should have the same dimensions, and
- Pillars at the edge of the panel should have the same stresses as those in the middle.

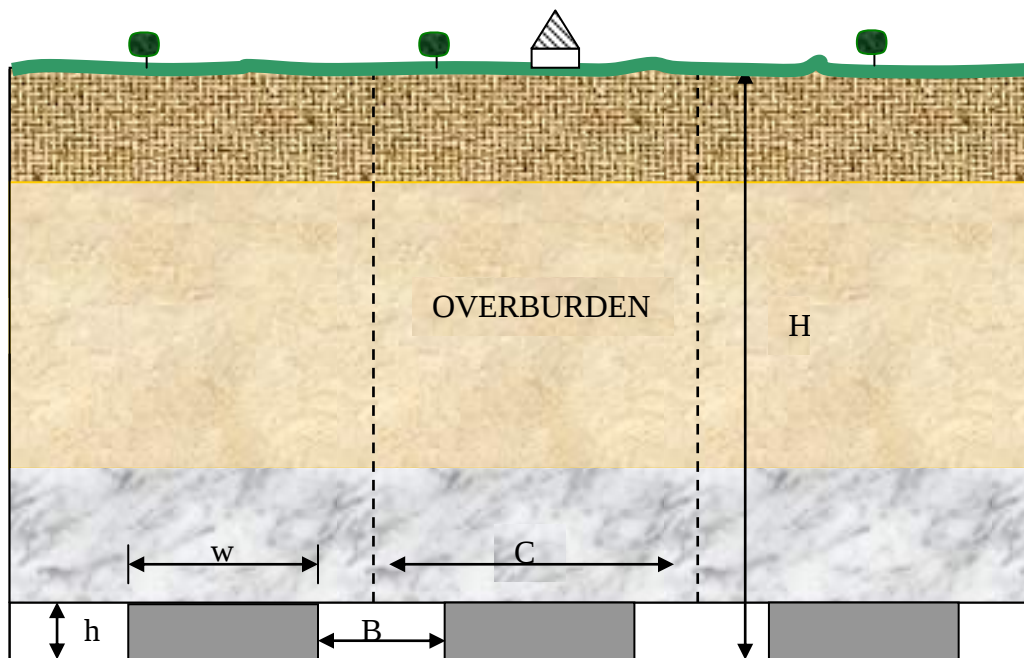
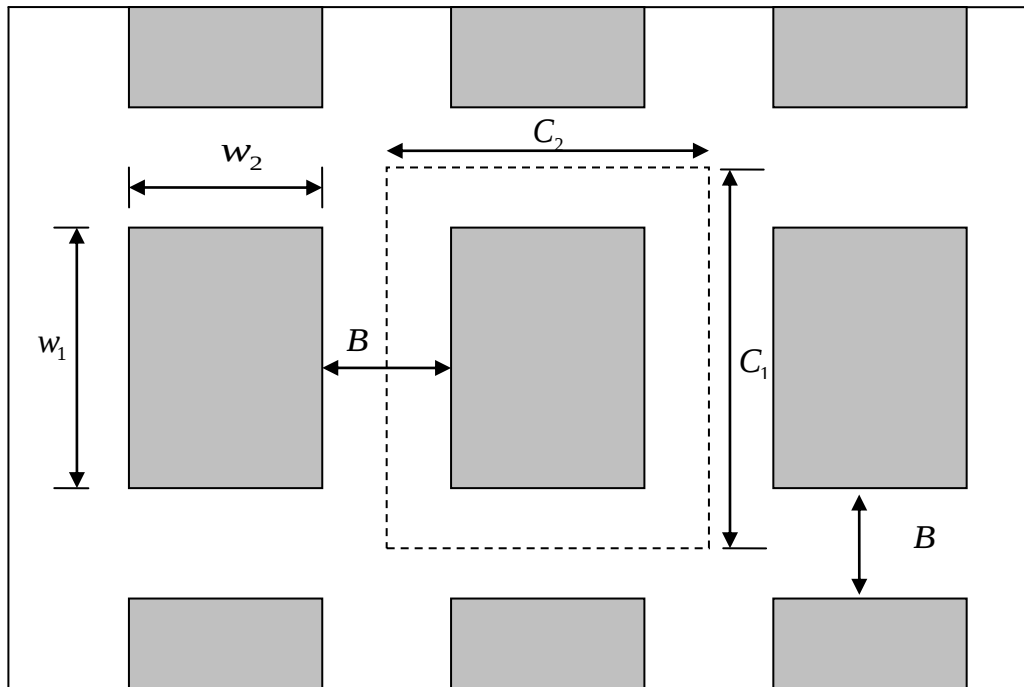


Figure 2.2: Illustration of the Tributary Area Concept

In figure 2.2,

B = Bord width

w_1 = pillar width in split direction

w_2 = pillar width in the direction of panel advance

$C_1 = w_1 + B$ (Centre distance in the split direction)

$C_2 = w_2 + B$ (Centre distance in the panel advance direction)

For square pillars: $w = w_1 = w_2$; $C = C_1 = C_2$

In the figure above, the load on the pillar, P , is, therefore,

$$P = (w_1 + B)(w_2 + B)\rho gH = C_1 C_2 \rho gH$$

Where: ρg = weight of the rock per unit volume; H = depth to floor of seam.

The stress on the pillar σ_p is given by:

$$\sigma_p = (P) / w_1 w_2 = (C_1 C_2 \rho gH) / w_1 w_2$$

Also note that, ρgH is the weight of overlying rock (vertical component of primitive stress). Taking ρ as 2.536 (tons/m³) and g as 9.81(m/s⁻²), the above equation becomes;

$$\sigma_p (kPa) = (25HC_1C_2) / w_1 w_2 \dots\dots\dots \text{Equation 2.1}$$

When the overburden material is composed of a dolerite, whose thickness is T, the pillar load will be given by (Van der Merwe and Madden, 2002):

$$\sigma_p = \{C_1 C_2 [25(H - T) + 30T]\} / w^2$$

The tributary area method ignores the deformation properties of the surrounding rock mass relative to pillar rock along with any rock failure, such as pillar yielding and associated stress re-distribution (Zipf, 2001). In a regular layout with pillars having the same dimensions, pillars around the centre of the panel have lower safety factors while pillars next to the barrier pillars have higher safety factors, because pillar size is based on the highest expected load while pillar loading increases from edge pillars to central pillars (Chugh et al, 2006).

In addition to the panel width to depth ratio, the percentage extraction and stiffness of the surrounding strata influence the validity of the tributary area method (Roberts et al, 2002). Van der Merwe et al (2003) stated that while the application of the tributary area theory is conservative from the point of view of the evaluation of the stability of pillars inside the panel, it results in an over optimistic view of the load on the inter panel pillars (barrier pillars).

However, Roberts et al (2002) mention that for practical design purposes, the suggested equations for average stress calculations are acceptable if the designer appreciates the limitations.

(b) The pressure arch theory

The pressure arch theory (illustrated in figure 2.3 below) states that as soon as an opening is made, the vertical load directly above the opening shifts outward to both sides of the excavation, leaving a de-stressed or relaxed zone in the roof strata (Holland, 1973). The exact shape and size of the arch depends on the stress levels, age and shape/size of an opening.

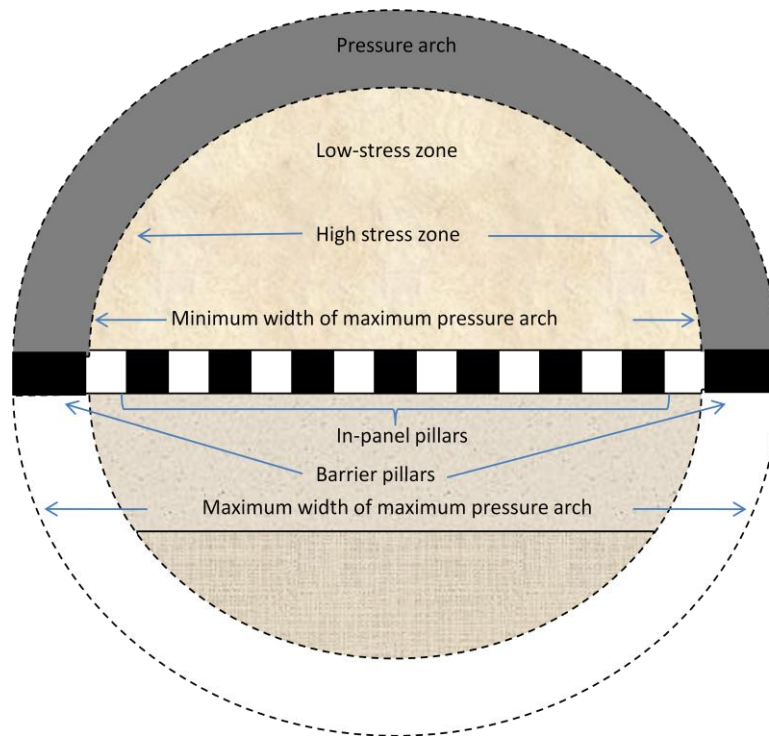


Figure 2.3: Conceptual illustration of Maximum Pressure Arch (Koehler and Tadolini, 1995)

If the width of the opening is progressively increased, the pressure arch becomes larger and larger until some limit is finally reached where the roof will break and thus the weight of the high beds will not be transferred to the sides of the opening

(Chamber of Mines of Zimbabwe, 1996). The width of the opening just short of this point is termed the maximum pressure arch. Observations of many mines have resulted in an empirical representation of the maximum arch for depths between 120 to 600m:

$$W = 0.15D + 18.3$$

Where W is minimum observed width of the maximum pressure arch (metres) and D is the depth of the seam in metres.

Although the pressure arch theory is a rule-of-thumb (Peng, 1986), it offers an important design concept for yield pillars. Here, pillars in a panel are designed to not take the full load. Instead, they are slightly under-designed. This causes the pillars to yield, thereby transferring their load to the barrier pillars or to larger pillars in the same panel. This concept aims to extend the benefits of the pressure arch theory to the current mining activities rather than to future mining activities (Schissler, 2002).

2.5.2 Estimation of pillar strengths

According to Van der Merwe and Madden (2002) a lot of research work on the strength of coal pillars over the years has addressed two important issues:

- The size effect - strength decreases as specimen size increases.
- The shape effect - the strength increases as the width to height ratio increases.

Thus, pillar strength formulae are generally a function of the width (w) to height (h) ratio and the coal strengths and they usually follow one of the two general forms shown in table 2.1 below:

Table 2.1: The two general forms of empirical pillar strengths formulae

Formulae	Notes
$\sigma_s = \sigma'_s \{(a + b(w/h))\}$ <i>Obert and Duvall (1967), Bieniawski (1968)</i>	σ_s = strength of the pillar; σ'_s = strength of a cubical pillar with a width to height ratio of one unit; a and b are appropriately chosen parameters. σ'_s, a and b were determined as 6.2MPa, 0.64 and 0.36 respectively (Bieniawski, 1968)
$\sigma_s = kw^\alpha h^\beta$ <i>Holland (1964), Salamon and Munro (1967)</i>	σ_s = strength of the pillar; k = is the constant characteristic of the pillar; α and β are appropriately chosen parameters. k, α, β were determined as 7.2MPa, 0.46 and -0.66 (Salamon and Munro, 1967)

Efforts to determine the strength of full scale coal pillars using laboratory experiments have been fruitless due to the variability of coal strength and the complex influence of size and shape on the strength of pillars (Van der Merwe and Madden, 2002).

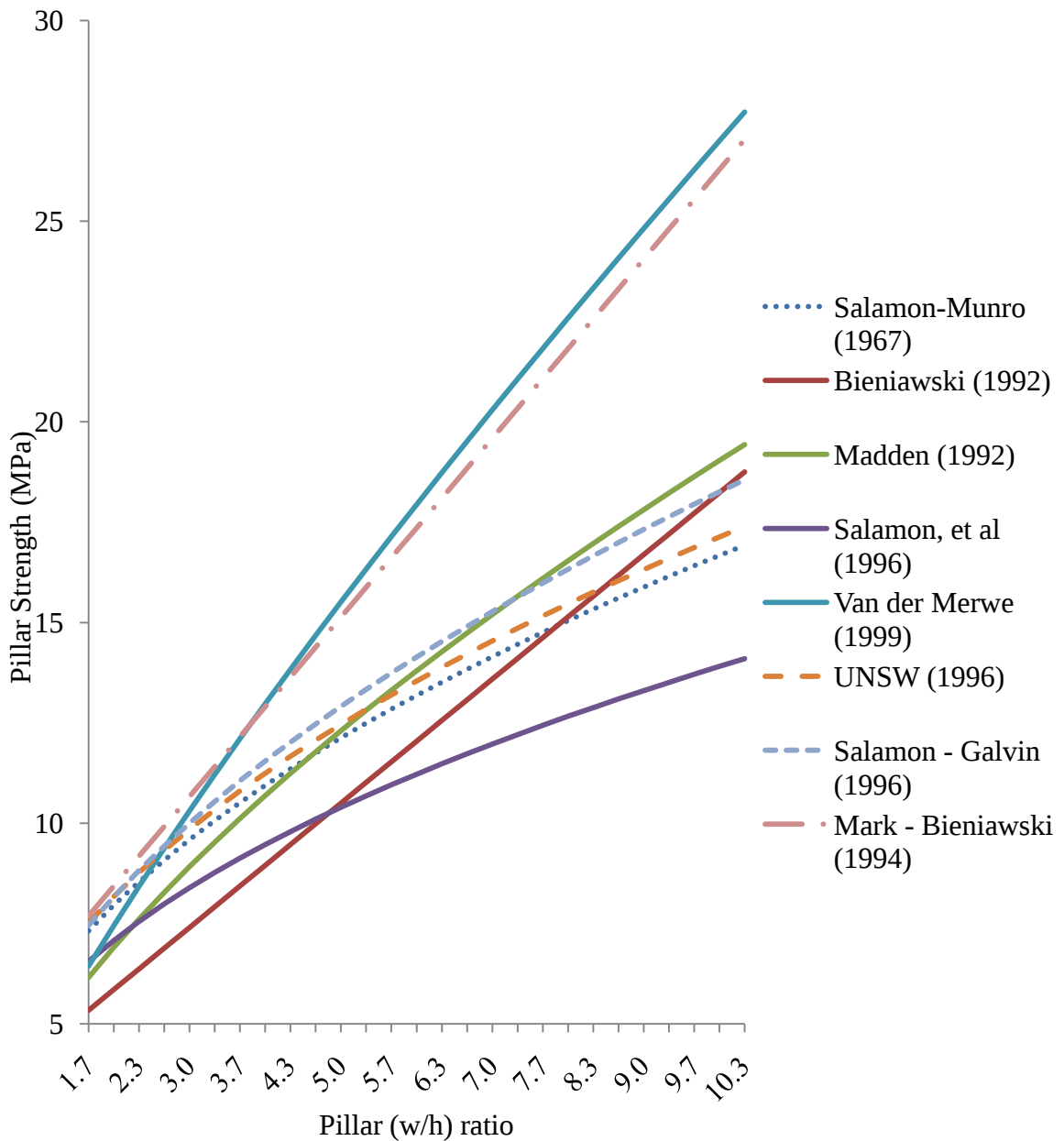


Figure 2.4: Different pillar strengths for a 3m high pillar obtained by using different equations

There are a number of empirically based mathematical equations for mine pillar design (Figure 2.4). The most reliable and extensively utilised formula is that developed in 1967 by Salamon and Munro (equation 2.2) for the strength of coal

pillars in South African mines following the Coalbrook disaster in 1960. This formula was applied to Australian conditions by the University of NSW in 1995 and found to agree to within 3% (Galvin, et al, 1999).

$$\sigma_s = 7200w^{0.46} / h^{0.66} \dots\dots\dots \text{Equation 2.2}$$

Where, h is the mining height, w is the width of the square pillars. For rectangular pillars, an effective pillar width w_e given by $w_e = 4A/C$ (Wagner, 1980) is used, where A and C are the pillar area and circumference respectively.

The Salamon and Munro formula was derived making use of a database of failed and stable pillar cases. While the method has received wide acceptance, Taylor and Fowell (2003) mention that Salamon did not specifically state that his design formula would be suitable for assessing the permanent stability of bord and pillar workings.

The formula was considered to be very conservative at width-to-height ratios greater than 5. In 1982 Salamon proposed an extension to his original formula (equation 2.2) to account for the increased strength of high pillar width to mining height geometries. Laboratory tests, field trials and in situ measurements were conducted to observe the performance of the squat pillars (Madden, 1991). This resulted in the formulation of the squat pillar strength formula given below:

$$\sigma_s = k(R_o^b / V^a) \{ (b/\varepsilon) [(R/R_o)^\varepsilon - 1] + 1 \}$$

Where:

$$k = 7\,200 \text{ kPa}$$

$$R_o = \text{critical width-to-height ratio (5.0)}$$

$$R = \text{pillar width to mining height ratio} > 5$$

$$\varepsilon = \text{is the rate of strength increase (2.5)}$$

$$\alpha = 0.0667$$

$$b = 0.5933$$

$$V = \text{pillar volume } (w_1 w_2 h)$$

The squat formula takes cognisance of the increasing ability of a pillar to carry loads with increasing (w/h).

According to Van der Merwe (1993), the strength of coal from various areas varies, for example the coal in the Vaal Basin has lower strength than that found in the Witbank area. Equation 2.2 was then changed to:

$$\sigma_s = 4.5(w^{0.46} / h^{0.66})$$

for the coal in the Vaal Basin

In 2001 Van der Merwe published a new strength formula for South African coal;

$$\sigma_s = k(w/h)$$

where k is a value between 2.8 and 3.5Mpa and w and h are the pillar width and mining height respectively.

Van der Merwe (2001) mentions that the differences in the strength formulae were due to two variables, namely the different approaches that were used by researchers and the differences in the databases.

Madden and Canbulat (1995) acknowledge that coal pillar strength is a function of many parameters including: geology, discontinuities, seam strength, time, weathering, loading rate and the surrounding strata properties. They further mention that where one of these parameters becomes dominant, the stability of the pillar system may not be predicted by the current pillar design methodology.

2.5.3 Evaluation of pillar stability

The empirical coal pillar factor of safety approach is considered to represent the most reliable methodology available for analyzing the long-term stability of pillars, in regular arrays, that are wide with respect to cover depth (Hill, 2005 and Salamon et al, 2006). The classical engineering approach is to design to a safety factor, where safety factor SF is defined as the ratio of the strength of the pillar (equation 2.2) to the load acting on the pillar (equation 2.1), and i.e.

$$SF = \sigma_s / \sigma_p$$

Substituting equations (2.1) and (2.2) into above, the safety factor is given by:

$$SF = 288w^{2,46} / (Hh^{0,66}(w+B)^2) \dots\dots\dots \text{Equation 2.3}$$

Table 2.2 and figure 2.5 illustrate the factors used for the determination of pillar stability.

Table 2.2: Estimates of pillar failure (Salamon and Munro, 1967)

Factor of Safety	Probability of Stable Geometry	No. of collapses in 1 million
2.1	0.999999	1
2.0	0.999994	6
1.9	0.999974	26
1.8	0.999894	106
1.7	0.999586	414
1.6	0.998464	1536
1.5	0.994700	5300
1.4	0.983000	17000
1.3	0.950800	49200
1.2	0.874800	125200
1.1	0.725900	274100
1.0	0.500000	500000
0.9	0.253400	746600
0.8	0.079900	920100
0.7	0.006600	993400
0.6	0.006000	994000

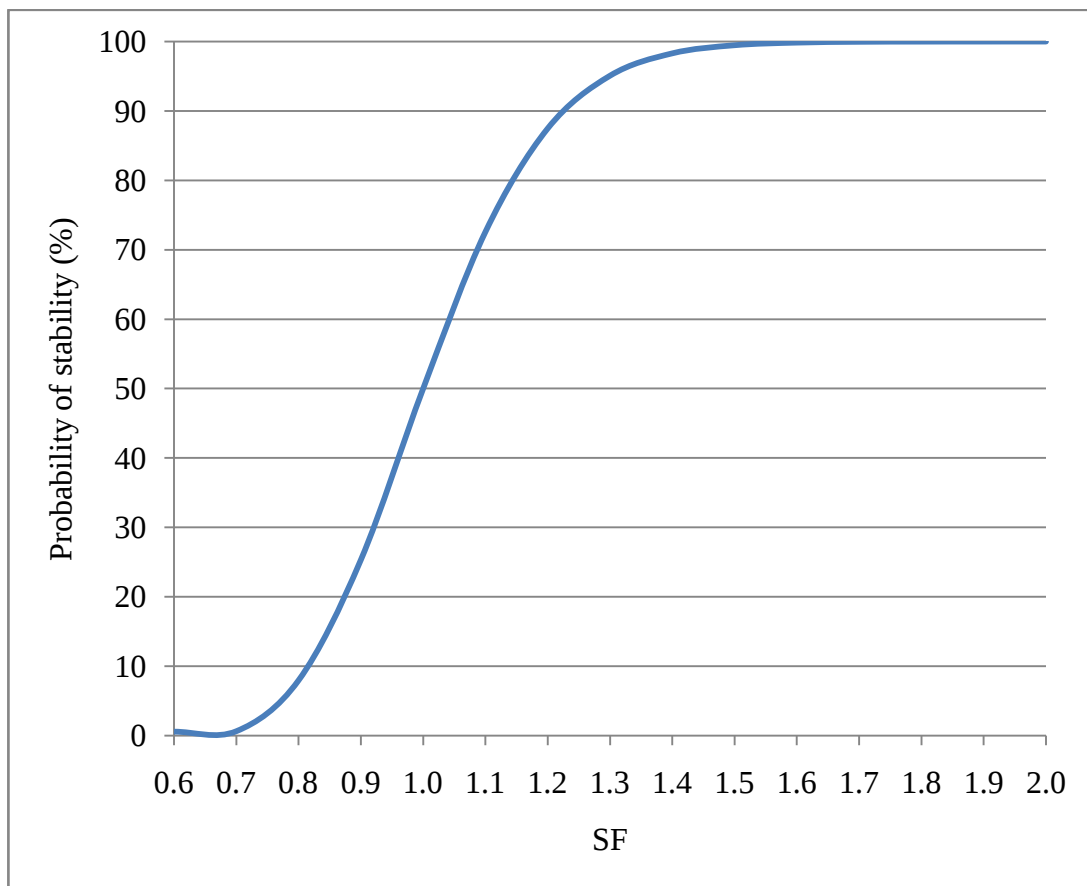


Figure 2.5: Probability of pillar failure as a function of safety factor (Salamon and Munro, 1967)

In the ideal situation of perfect formulae and material properties, a safety factor just greater than 1 (that is, 1.0001) would imply that the design would be stable, but just less than (0.9999) would imply that it would be unstable. An acceptable safety factor depends on the tolerable risk of failure, for example:

- A safety factor of 1.8 is typical in main development headings or panels during advance mining.
- Safety factors between 1.1 and 1.3 are typical for panel pillars after retreat mining.

- Safety factors of less than one are possible within panels where pillar failure is the intent.

According to Nzenga (1998) the choice of a suitable safety factor to guard against pillar failure is based upon engineering experience and various authors recommend different safety factors for different applications.

From the work of Salamon and Munro (1967), safety factors of collapsed pillars ranged from 0.9 to 1.5. A safety factor of 1.6 was taken as an acceptable safety factor in most mining situations. Local mining conditions should be taken into account in deciding on the pillar factor of safety.

Chugh et al (2006) mentions that safety factors vary within the panel because stress distribution across a panel is non-uniform. In the design of a pillar, a factor of safety is provided to take care of the errors in the computation of strength and load on pillars.

All pillar collapse cases used in Salamon and Munro's (1967) back analysis were mined by the drill and blast method and the influence of the blast damage on the pillar side is included in the original formula (equation 2.2). To account for the lack of blast damage in a pillar formed by continuous miner, Wagner and Madden (1984) suggest the following equation:

$$\eta = \eta_o (1 + \{2\Delta w_o/w\})^{2.46}$$

Where:

- η is the safety factor of a continuous miner formed pillar
- η_o is the safety factor of a drill and blst formed pillar
- Δw_o is the extent of blast damage (0.3m)
- w is the nominal pillar width

Madden and Hardman (1992) established the following guidelines for mining at depths less than 40m below surface, if Salamon's formula is to be applicable:

- Extraction should not be more than 75%
- Safety factor should not be less than 1.6
- The bord width should not be greater than 7m
- Pillar width should not be less than 5m
- The (w/h) ratio should be greater than 2

2.6 Barrier Pillar Design

2.6.1 Functions of barrier pillars

Barrier pillars are required to prevent possible collapse of panel support pillars in underground coal workings from spreading to adjacent workings (Esterhuizen, 1991).

According to Esterhuizen (1991), the importance of a barrier pillars in the stability of bord and pillar workings was recognized in the 1960's when a large area of the Coalbrook Colliery collapsed. As a result of the lack of strong barrier pillars the collapse of pillars in one area resulted in the overloading of adjacent pillars and the collapse spread over an area of 4 km² with the loss of over 400 lives. Esterhuizen (1992) suggested using the confined core approach as a realistic estimate for the strength of barrier pillars.

Nzenga (1998) defines barrier pillars as pillars with a width to height ratio of about 10 which provide regional support to mine workings and are expected to remain stable during the life of the mine.

There are two types of continuous barriers found in collieries (Rangasamy et al, 2001);

- those found on the boundary between neighbouring mines as required by law
- those found in between panels and / or areas on a mine

Barriers found in between panels have the following primary functions (Rangasamy et al, 2001):

- Create panels with independent pillar design parameters
- Prevent and contain regional pillar collapse through isolation of workings
- Minimize the effect of high abutment stresses on roadways and influence ground control in adjacent panels
- Control strata and surface subsidence
- Create independent ventilation districts
- Isolate development panels so they can easily be sealed off
- Act as ventilation and water barriers

2.6.2 Design methodologies

The design approach for barrier pillars has been based on a relationship between the width of the barriers and those of the adjacent workings. The width of the barrier depends on the load which it has to carry and its strength. The greater the depth of workings, the wider the barrier and also the softer the coal, the greater the width of the barrier. Figure 2.6 gives barrier pillar widths for different design methods. In practice the width of the barrier enclosing pillars is usually the same as the width of the coal pillars which are enclosed within the panel (Singh, 1997).

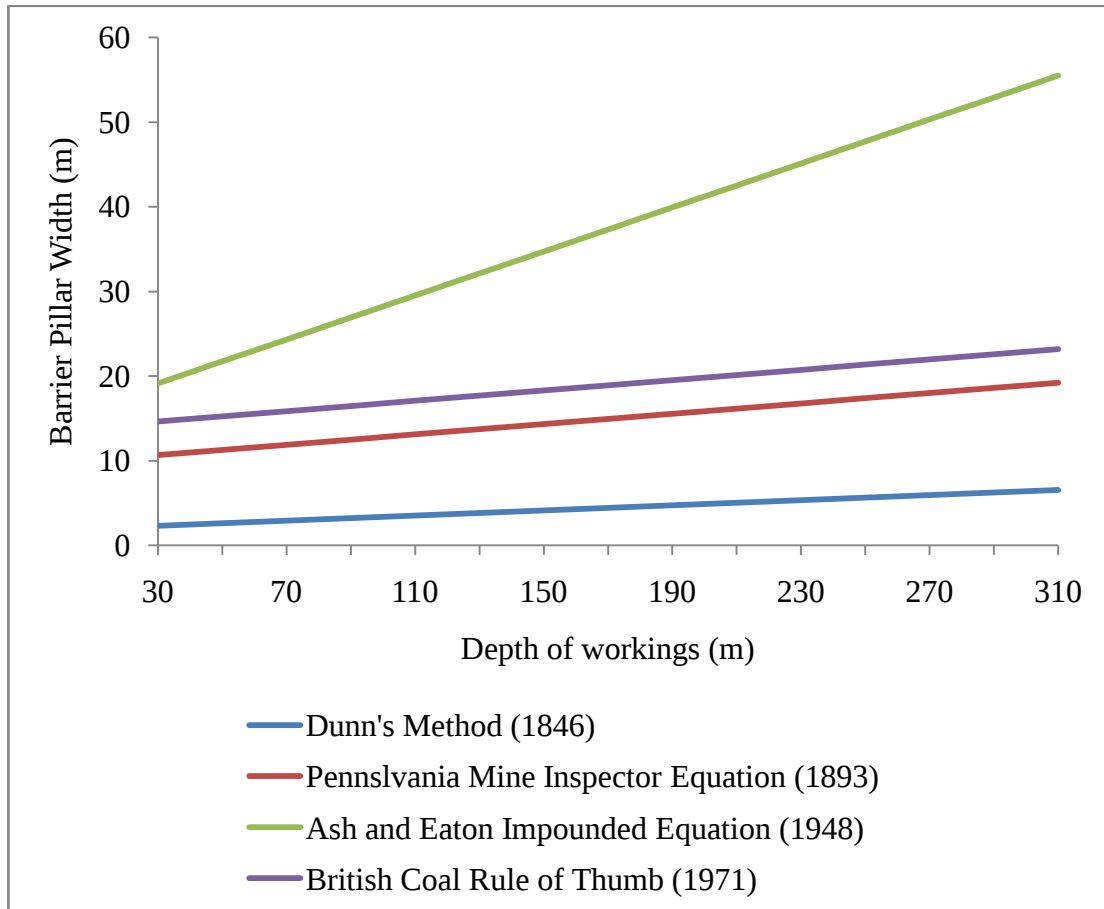


Figure 2.6: Relationships between barrier pillar width and depth of workings using different equations

Van der Merwe (2006) mentions that little has been done to determine the strength of barrier pillars in coal mining in South Africa. Until 1993 there were no formulae for determining the width of barrier pillars that are meant to contain a collapse from spreading to adjacent panels. Current practices in the design of barrier coal pillars are based on the fact that the barrier pillars are related to the width of the pillars in adjacent workings. A booklet on the hydraulic design of coal barrier pillars, Rangasamy et al (2001), discusses the international and South African design approaches, summarized in the Appendix.

What becomes of concern is the effect of the width of the barrier pillars on the overall stability of the panel and consequently on the extraction rate. Barrier pillars should be able to resist increased loads imposed on them. A study conducted by Esterhuizen (1991) revealed that barrier pillars which were as wide as adjacent panel pillars were able to arrest a collapse. Their effectiveness decreases with increasing width of the panel pillars. The load on the barrier pillars was found to depend largely on the behaviour of the overlying strata.

2.7 Roof Support

2.7.1 Mechanism of roof behaviour

As bord and pillar workings are developed roof support becomes a major consideration for the miner. Roof support has three primary functions:

- To prevent major collapses of the mine roof;
- To protect miners from small rock falls that can occur from the immediate roof skin; and

- To control deformations so that mine openings remain serviceable for both access and escape, as well as for ventilation of the mine workings.

Once an opening is created underground, the portion of the strata directly above the opening loses its original support, the stresses are disturbed (Canbulat and Madden, 2004), and the roof starts to sag under the gravitational force. Van der Merwe and Madden (2002) mention the bord width as one of the main controllable parameters for the roof. A reduction in the size of the in-panel pillars in an attempt to increase production results in an increase in the amount of sag, given by the equation:

$$\eta = (\gamma L^4) / (32Et^2) \dots\dots\dots \text{Equation 2.4}$$

Where;

γ	=	unit weight of the roof material (MN/m ³)
η	=	amount of sag in the roof (m)
L	=	span (bord width) (m)
E	=	modulus of elasticity of roof material (MPa)
T	=	thickness of the roof beam (m)

Equation 2.4 shows that deflection is proportional to the fourth power of the bord width. The equation highlights the importance of thickness and span of a beam on the maximum deflection of the beam and stresses at the end of the beam (Haile et al, 2007). The equation can be applied where the underground conditions are well known and the failure mechanism understood. According to Van der Merwe and Madden (2002), increasing the road width from 6.6m to 7.8m will double the amount of sag.

Buddery and Oldroyd (1992) mention that roof failure in South African coal mines is predominantly governed by the frequency of laminations or bedding planes and their propensity to separate, and by the bord width. The creation of a stable beam for the

roof is achieved by roof support installation that involves: suspension of thin or weak roof layers from a massive bed; beam building; or the formation of a rock arch.

Wilkinson and Canbulat (2007), have identified and investigated five important components of a support system as: resin, bolt, hole, equipment and rock type. They mention that failure in any of these components will result in an inadequate support system.

2.7.2 Roof support design methods

Roof support design is currently based on utilizing past experience, empirical design based on Rock Mass Classification of the roof strata, the application of models such as suspension, beam creation or the formation of a rock arch, instrumentation or a combination of these techniques (Haile et al, 2007).

(a) Weight suspension design

This design procedure requires that the bolt system's support capacity must exceed the weight of the laminated material, that the spacing of bolts is dense enough to prevent falls between bolts and that the overlying sandstone beam must be thick enough to support itself plus any softer overlying layers and the laminated material suspended underneath.

The number (n) of bolts per square metre required to support loose layers of thickness, t , is given by:

$$n = SF\rho gt / Pf \dots\dots\dots \text{Equation 2.5}$$

Where:

SF	=	<i>safety factor (minimum 1.5)</i>
ρ	=	<i>density of suspended strata (kg / m^3)</i>
g	=	<i>gravitational acceleration ($9.81 \text{ m} / \text{sec}^2$)</i>
Pf	=	<i>yield load of bolt (kN)</i>
t	=	<i>beam thickness (m)</i>

The area (A) that may be supported by one bolt will be given by the reciprocal of n . The required bolt spacing is determined by the square root of the area.

(b) Beam creation design

Beam creation is a form of roof support usually applied to thick laminated roof where the cohesion and friction between layers are sufficient to allow the laminated zone to behave like a single beam (Van der Merwe, 1998). The following pre-requisites are required prior to implementing this design method:

- Bolts have to be installed before the roof layers have started to sag or separate
- The support material used and the roof bolting equipment must allow the required amounts of pretension to be applied to the roof.

The amount of roof sag as mentioned earlier depends on the road width (equation 2.4), advance before bolts are installed and time lapse between exposing the roof and installing the bolts. The installed bolts act as pins and by tensioning them, they increase the normal stress on the layers to enhance the natural frictional resistance between the layers.

(c) Suspension of thick weak roof design

This philosophy accepts that the roof will fail and merely supplies a basket in which loose roof can be contained without causing damage. It includes standing supports, long cable anchors and short inclined bolts or trusses.

2.7.3 Instrumentation

Instrumentation is used to monitor displacement, strata separation or roof bolt load transfer. The objective may be to gain scientific information, to monitor the efficiency of the support system or to be aware of changes that occur in the roof (Van der Merwe, 2003). Displacement is measured by extensometers installed in the roof and the relative movement of the anchors recorded (Haile et al, 2007). This provides an assessment of the relative performance of support systems. Haile et al (2007) mention that this method is acceptable for monitoring laminated beams in the centre of the roadway, but does not measure lateral displacement. Precise survey techniques can accurately monitor the roof behavior. A borescope is used to measure the position of strata separation within a borehole.

2.8 Production Consideration

2.8.1 Extraction versus depth in bord and pillar workings

Due to the increasing pressure encountered with depth, the bord and pillar method requires progressively larger pillars resulting in reduced recoveries, as indicated in Figures 2.7 and 2.8 below:

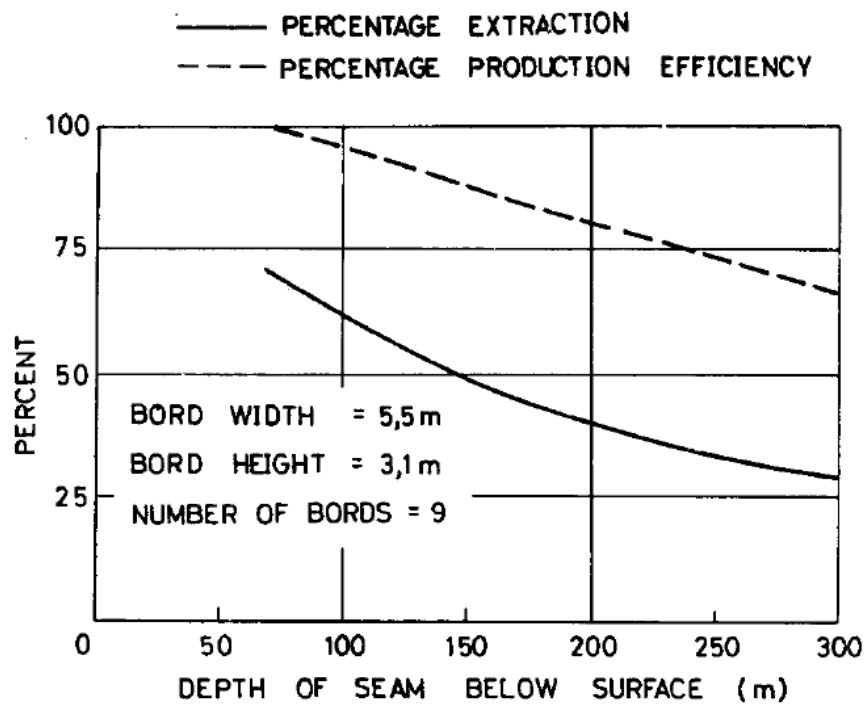


Figure 2.7: Effect of depth of mining on percentage extraction and productivity in bord and pillar mining (Wagner, 1980)

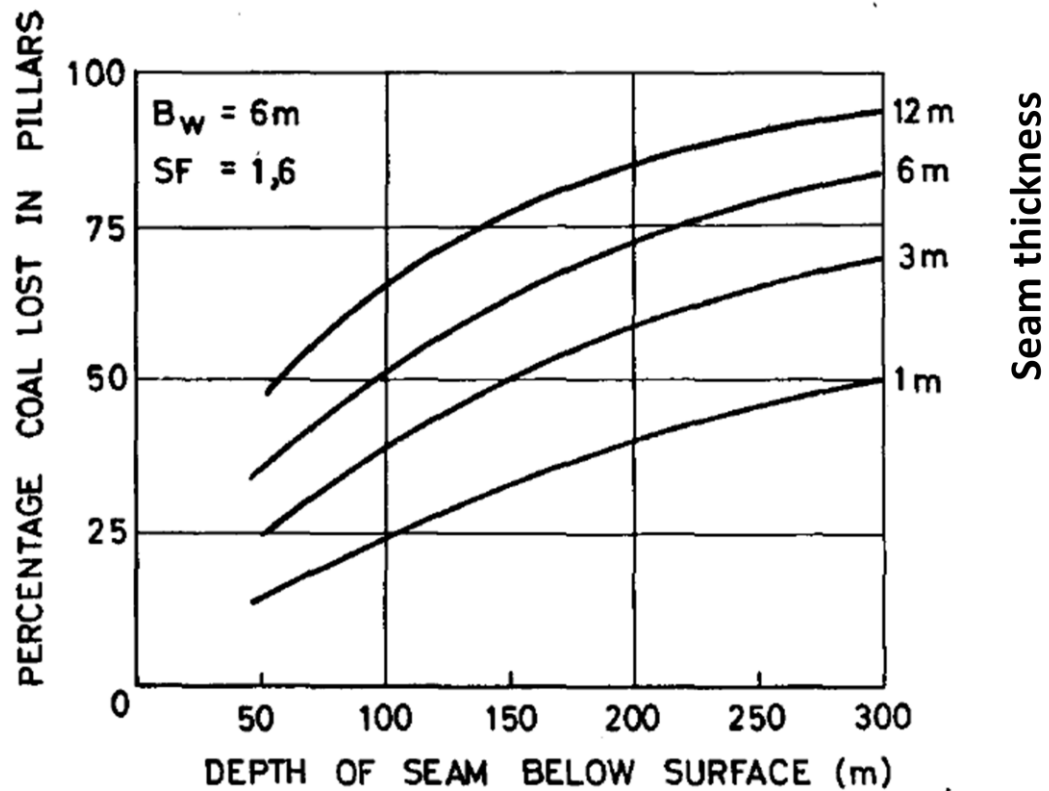


Figure 2.8: Effect of depth below surface and seam thickness on coal losses in bord and pillar mining (Wagner, 1980)

The design of pillars goes hand in hand with production considerations. While large pillars normally have higher safety factors, production in terms of the extracted coal is compromised. The pillar size should be neither too small to support the overburden load nor too large to reduce mining productivity.

From figure 2.2, the areal extraction for square pillars, is given by

$$e = (C^2 - w^2) / C^2 = 1 - (w^2 / C^2) \dots\dots\dots \text{Equation 2.6}$$

This is a geometrical ratio which is a direct result of mine planning (King, 1980). It is related to the pillar load by the expression;

$$\sigma_p = [0.025H / (1 - e)] MPa$$

In order to increase recovery in bord and pillar mining, a mine may be planned such that when a panel has advanced to a barrier pillar line, retreat mining then follows. Recovery has also been improved by working panels on two passes; leaving long rectangular pillars in the advancing phase, splitting the pillars on retreat.

The volumetric extraction rate, r is given by the volume of the mineable coal V_m divided by the volume available in the area V_c . For a square area;

$$V_m = h(C^2 - w^2)$$

$$V_c = mC^2, \text{ where } m \text{ is the thickness of the coal seam}$$

Therefore;

$$r = (h / m)(1 - (w^2 / C^2)) = h_e m$$

$$h_e = \text{ratio of equivalent working height}$$

Maximum volumetric extraction is obtained with an increase in mining height.

2.8.2 Influence of barrier pillars on extraction

When barrier pillars are taken into consideration, the overall areal extraction, e_o becomes:

$$e_o = 1 - \left\langle \frac{\{Cl + (n-1)w^2\}}{\{C[l + (n-1)C + B]\}} \right\rangle \dots\dots\dots \text{Equation 2.7}$$

Where;

n = number of bords, l = width of barrier pillar, w = pillar width,

B = bord width, and C = pillar centre distance

Figure 2.8 shows the relationship between overall extraction and number of bords for different in-panel pillar sizes.

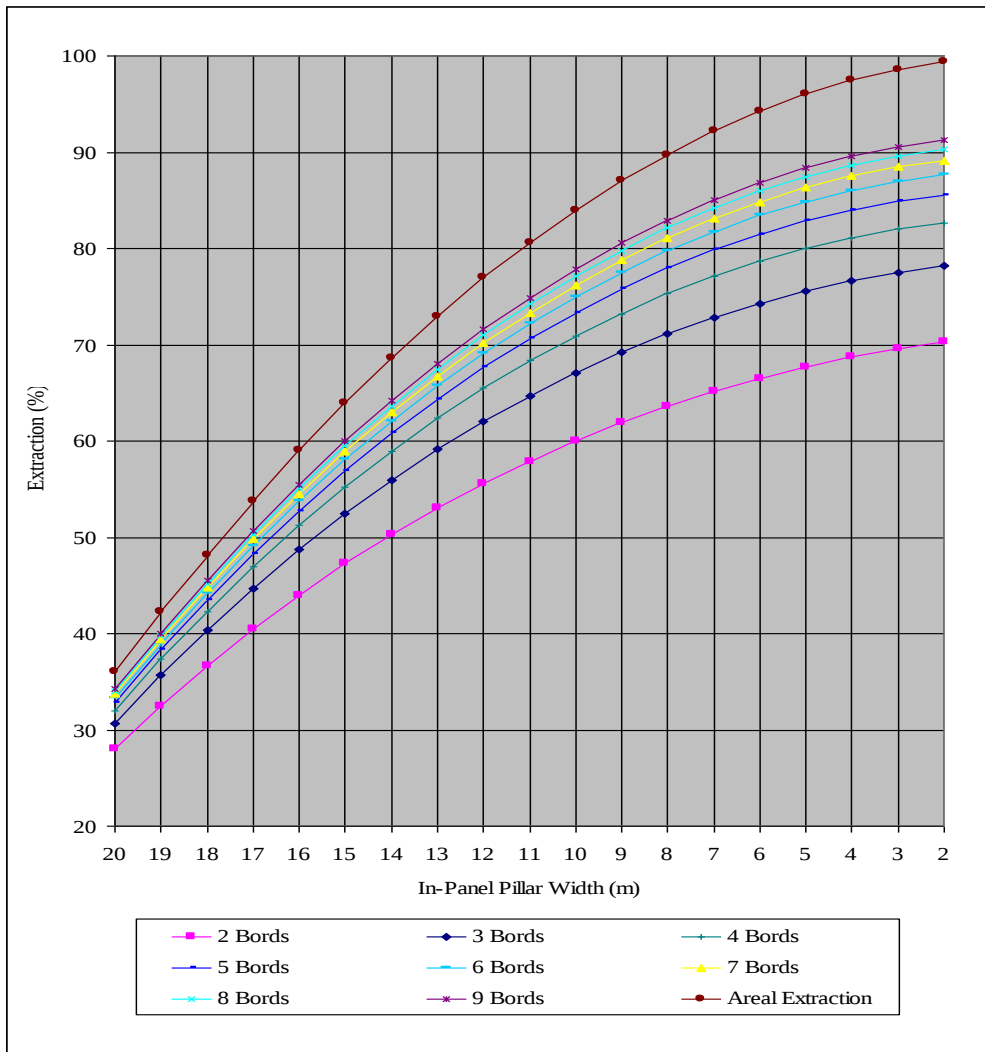


Figure 2.9: Overall extraction as a function of number of bords and in-panel pillar width

2.9 Conclusion

This chapter has discussed in detail the empirical methodology of coal pillar design that has been developed over the years. While previous research has highlighted that stress in a panel is not uniformly distributed, the empirical approach does not give an indication of the application of this into new system designs. The effect of the barrier pillars on the in-panel pillars has received very little attention and equal sized pillars continue to be used in present designs. If the methods have taken cognisance of this, then it would have been possible to have different formulae which depend on the location of the pillars (adjacent to barrier pillar or at the centre of a panel) for determining their stability in terms of stress, strength and the resulting safety factor.

It becomes necessary to employ numerical techniques in investigating the possibility of increasing extraction through analysing the unequal distribution of stress across bord and pillar primary extraction panels. Numerical modelling of bord and pillar layouts of various barrier and in-panel pillar sizes at different depths are described in the next chapter.

CHAPTER 3

Numerical Modelling

3.1 Introduction

The previous chapter has concentrated on empirical work on the subject of coal pillar design and it has been seen that the interaction of barrier and in-panel pillars has not been adequately addressed by these methods. This chapter focuses on the application of numerical modelling to this problem. A description of the selected software package (Lamodel) for the project is given and an initial investigation into the loading of barrier and in-panel pillars is instituted through analysis of vertical stress, safety factor and seam convergence. The result of the investigation may find application in the design of alternative bord and pillar layouts that offer improved extraction under stable conditions.

3.2 Numerical Approach to Pillar Design

Although mine planners have a variety of empirical methods available for analyzing pillar stresses and determining safe pillar sizes for various mine geometries, when complicated stress conditions arise from complex single or multiple seam geometries, numerical modelling techniques such as finite-element, boundary element, or finite-difference methods are usually applied (Heasley and Agioutantis, 2001). There are a number of programmes designed from the fundamental laws of force, stress and elasticity that are available for simulation of underground workings (Singh and Farmer, 1985).

In numerical modelling, a pillar is analysed as a complex structure with a non-uniform stress gradient, a buildup of confinement around a high stress core, and

progressive pillar failure. Numerical modelling for coal mine ground control requires an understanding of the complex mechanical behaviour and properties of rock.

According to Jaiswal et al (2004), the primary advantage of numerical models is that they can quickly analyze the effects of numerous geometrical and geotechnical variables on the mine design. Overall, there is increased accuracy and enhanced design in the application of numerical modelling.

The disadvantage of numerical modelling is that it requires numerous assumptions about material properties, failure criteria and post-failure mechanisms (Gale, 1999). Heasley and Agioutantis (2001) mention that one of the most difficult aspects of using numerical models is determining the correct (most accurate) material properties. However, Coulthard (1999) stipulates that if extensive geological and geotechnical data are not available for comprehensive predictions of deformations, numerical models can still be used to perform parametric studies, providing the likely range of responses of a system.

A number of researchers have contributed in the field of numerical methods for modelling coal pillars. A few examples are given below:

- To assess in situ stress and abutment loads, Kendorski and Bunnell (2007) developed a site-specific model of the proposed barrier design using a displacement –discontinuity code called EXPAREA and evaluated stability of the barriers according to abutment loading predicted by modelling.
- In a numerical modeling study of asymmetry in the induced stresses over coal mine pillars with the advancement of the goaf line, Jaiswal et al (2004) concluded that the central portion of the pillar at the roof level experiences the least induced stress; whereas pillar corners experience the highest stress.
- Roberts et al (2002) conducted a numerical investigation to determine the loads on pillars in a typical bord-and-pillar coal mining panel and compared

them to the tributary area theory. Their conclusion was that the tributary area formula was a reasonable estimation of load for the failed cases, though loads are under-estimated in some cases. They emphasize that the stress on a pillar in a horizontal seam cannot exceed that predicted by the tributary area theory.

- The US National Institute of Occupational Safety and Health (NIOSH) has developed ARMPS, ALPS, MULSIM/NL and LAMODEL computer software for assessing pillar stability in different coal mining situations.

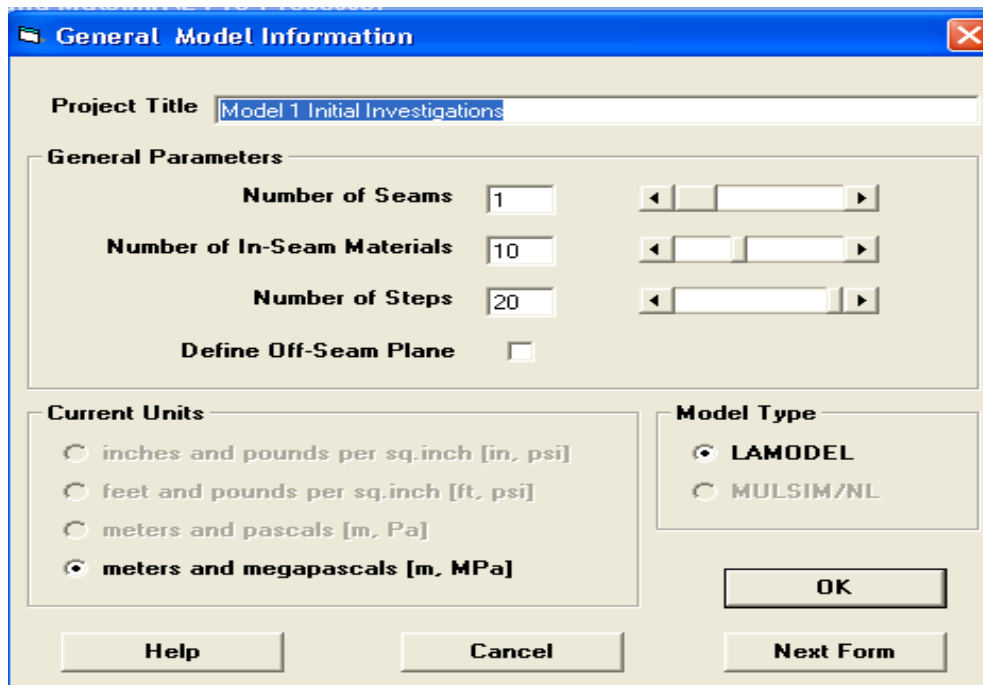
In order to analyze the displacements and stresses associated with extraction of large tabular deposits such as coal, the displacement-discontinuity variation of the boundary element technique is frequently the method of choice (Heasley and Agioutantis, 2001). The main attraction is the relative ease of setting up the models and the speed of execution while providing sufficient accuracy for most mining applications (Van der Merwe and Madden, 2002).

3.3 Lamodel Programme Description and Application

LaModel is a pc based, three dimensional boundary element program for calculating stresses and displacements in coal mines or other thin, tabular seams or veins. It can be used by mine design engineers in the industry to investigate and optimize pillar sizes and pillar layouts in relation to pillar stress. The programme simulates the geological overburden stratifications as a stack of layers with frictionless interfaces (Heasley et al, 2001). Each layer is homogeneous, isotropic and elastic and has the identical elastic modulus, Poisson's ratio, and thickness. The formulation of LaModel is based on the theory of thin plates and it is assumed that beds are always parallel and that no cohesion is present along the contacts (Roberts et al, 2007).

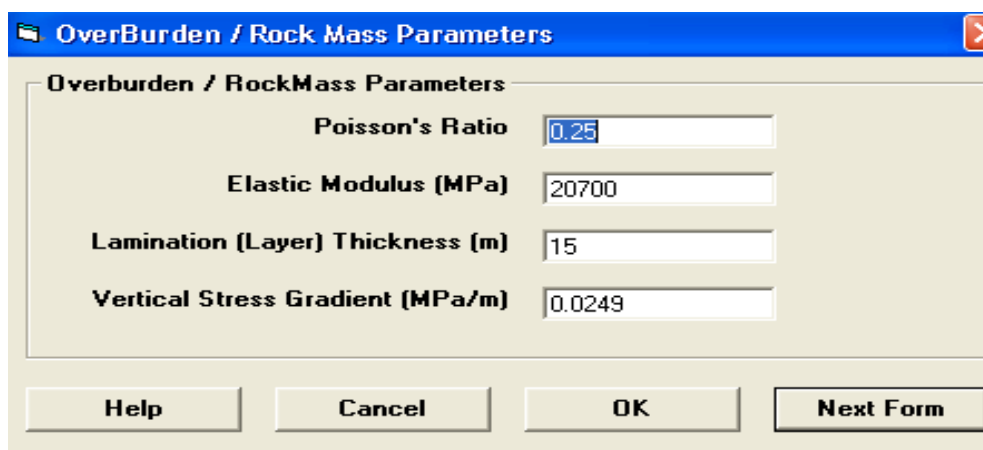
The LaModel package (NIOSH, 2007) consists of three separate programs (Figures 3.1 and 3.2), Lampre, Lamodel and Lamplt. Lampre is the pre-processor that

facilitates creating the input file for Lamodel which then calculates the stresses and displacements at the seam level from the input. Lamplt is the post-processor that allows the user to plot and analyze the output Lamodel.



The 'General Model Information' dialog box contains the following fields and controls:

- Project Title:** A text field containing 'Model 1 Initial Investigations'.
- General Parameters:**
 - Number of Seams:** A text field with '1' and a spinner control.
 - Number of In-Seam Materials:** A text field with '10' and a spinner control.
 - Number of Steps:** A text field with '20' and a spinner control.
 - Define Off-Seam Plane:** An unchecked checkbox.
- Current Units:** A group box with four radio buttons:
 - ☐ inches and pounds per sq.inch [in, psi]
 - ☐ feet and pounds per sq.inch [ft, psi]
 - ☐ meters and pascals [m, Pa]
 - ☒ meters and megapascals [m, MPa]
- Model Type:** A group box with two radio buttons:
 - ☒ LAMODEL
 - ☐ MULSIM/NL
- Buttons:** 'Help', 'Cancel', 'OK', and 'Next Form'.



The 'OverBurden / Rock Mass Parameters' dialog box contains the following fields and controls:

- Overburden / RockMass Parameters:**
 - Poisson's Ratio:** A text field containing '0.25'.
 - Elastic Modulus (MPa):** A text field containing '20700'.
 - Lamination (Layer) Thickness (m):** A text field containing '15'.
 - Vertical Stress Gradient (MPa/m):** A text field containing '0.0249'.
- Buttons:** 'Help', 'Cancel', 'OK', and 'Next Form'.

Figure 3.1: Typical parameter input forms for Lampre

(a) **Lampro**

(b) LaModel

The screenshot shows the LaModel software window. The title bar indicates the file path: C:\Documents and Settings\bang\Desktop\WSc Bambazonke\Chapter 3 Model 1a.INP. The interface is divided into several sections: 'Overall Progress' shows Mining Step 1 and Elapsed Time of 10 seconds; 'Seam Progress' shows Primary Seam 1, Secondary Seam 0, and Detail Level 3; 'SOR Iterations' shows Iteration Number 1400 and Maximum Displacement 0.0000001; 'Stress Projection' shows Gridline Number 0. At the bottom right, there are 'Run' and 'Exit' buttons.

(a) Lamplt

Figure 3.2: Lamodel package screen shots (a) grid editor in Lampre, (b) Lamodel calculations and (c) coloured square output in Lamplt.

LaModel provides a plan (top down) view of a mining area (Norwest Corporation, 2008). It uses the Mark-Bieniawski technical calculations to generate coal properties for pillar strength. The programme allows a more detailed analysis of effects of irregular shapes and dimensions from previously mined and projected mining areas.

Van der Merwe and Madden (2002), Roberts et al (2007) and various other authors have described an evaluation of the boundary element programme. It has been found to provide realistic stress and displacement calculations. Quiet recently, Norwest Corporation (USA) has applied it in investigating the instability of the Crandall Canyon Coal mine (2008) that led to the death of nine miners.

3.4 Numerical Investigations

3.4.1 Material characteristics and model design criteria

The modeling conducted in this research project is not based on any site-specific information; as such the parameters used are based on the default values for the Lamodel programme which have been determined to give reasonable overburden response (NIOSH, 1998).

The following material properties have been applied in the models investigated:

- **General Parameters:**
 - Number of seams 1
 - Units applied m, MPa
- **Overburden Rockmass Parameters:**
 - Poisson's Ratio 0.25
 - Elastic Modulus (MPa) 20700
 - Lamination (Layer) Thickness (m) 15
 - Vertical Stress Gradient (MPa/m) 0.0249

- **Seam Geometry:**
 - Element width 0.5m and 1.0m
 - Number of Elements in X axis 600
 - Number of Elements in Y 300
- **Seam Boundary Conditions:**
 - North Rigid
 - East Rigid
 - West Rigid
 - South Rigid
- **Seam Location:**
 - Overburden Depth (m) 50, 100, 150, 200
 - Seam Thickness (m) 3.0
- **Material Parameters:**
 - Coal Modulus (MPa) 2070
 - Plastic Modulus (MPa) 0
 - Coal Strength (MPa) 6.2
 - Poisson's Ratio 0.33

The design criteria definition as applied to the models investigated is as shown in table 3.1.

Table 3.1: Design criteria applied in the construction of base case models

Criteria	Model 1	Model 2	Model 3	Model 4
Depth, H (m)	50	100	150	200
Mining height, h (m)	3.0	3.0	3.0	3.0
Bord width, B (m)	7.0	7.0	7.0	7.0
Number of bords, n	9	9	7	5
Pillar width, w (m)	7.0	10.0	15.0	20.0
Pillar centres, C (m)	14.0	17.0	22.0	27.0
Barrier pillar width, BP (m)	7.0	10.0	15.0	20.0
(w:h) ratio	2.33	3.33	5.00	6.33
Pillar load (TAT), (MPa)	5.00	7.23	8.07	9.11
Pillar strength (MPa)	8.53	10.06	12.12	14.57
Factor of safety (CM)	2.09	1.61	1.65	1.72
Probability of stable geometry	0.999639	0.998646	0.999188	0.999685
In-panel extraction (%)	75.0	65.4	53.51	45.13
Overall panel extraction (%)	72.2	62.7	50.4	41.3

The above parameters all meet the requirements for the application of the Salamon formula and the primary development bord-and-pillar workings can be said to be stable since:

- Areal extraction is less than or equal 75%
- Bord width does not exceed 7m
- Safety Factors are greater than 1.6
- Pillar widths are greater than 5m

The following investigations were conducted on the four models given in table 3.1

- (a) Varying in-panel pillars for fixed barrier pillar size and location
- (b) Varying barrier pillars for fixed in-panel pillar size and location
- (c) Varying in-panel pillar positions (increasing bord widths)
- (d) Increasing barrier pillar widths for reduced in-panel pillars

Each model consists of three panels, separated by barrier pillars (Figure 3.3). For ease of reference, all the pillars have been named according to their location in the panel. Barrier pillars are named BP, in-panel pillars are named P1, P2, P3, P4 from the barrier pillars towards the centre of the panel.

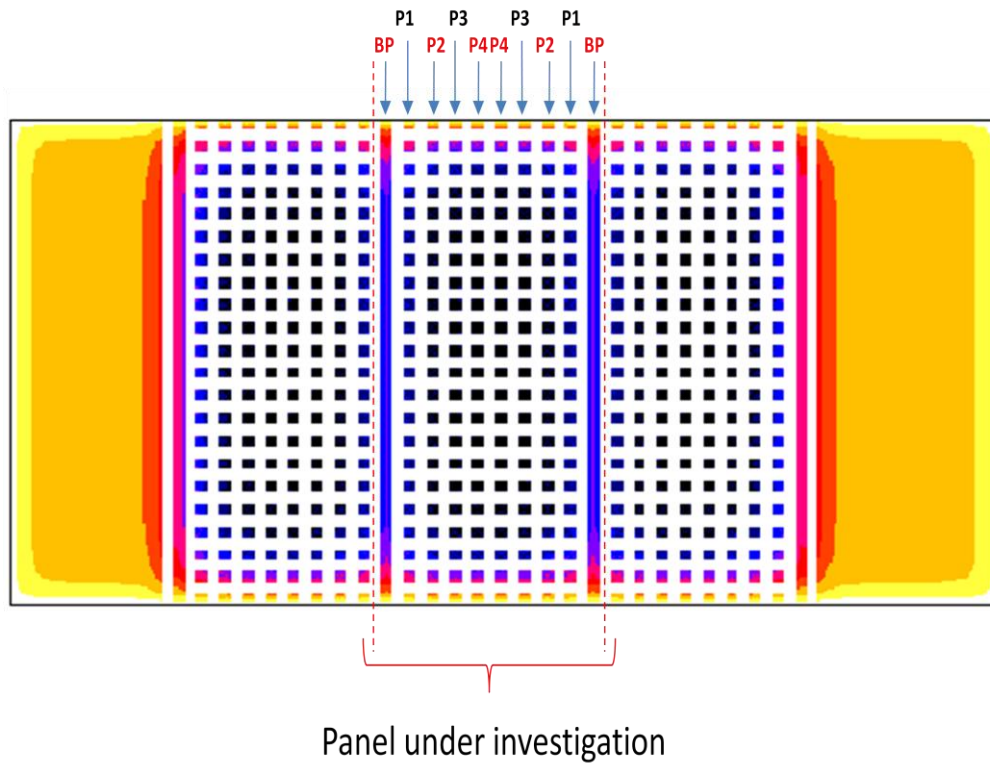


Figure 3.3: Illustration of panel under investigation

The grid generation programme for Lamodel can only take 1000 elements in both the X and Y directions, in order to present the three panels in each of the models an element width of 1m has been used. A width of 0.5m has been however applied to cases that require a smaller representation of area.

3.4.2 Varying in-panel pillars for fixed barrier pillar size and location

(a) Model description

In the model, a bord and pillar mining panel with the in-panel pillars having the same width initially as the barrier pillars, the pillar widths are then reduced by 0.5m and 1m at every step of the LaModel programme (Figure 3.4). The process is done for different numbers of roadways (bords) starting from 2 to 9 at mining depths of 50m, 100m, 150m and 200m at a fixed mining height of 3m.

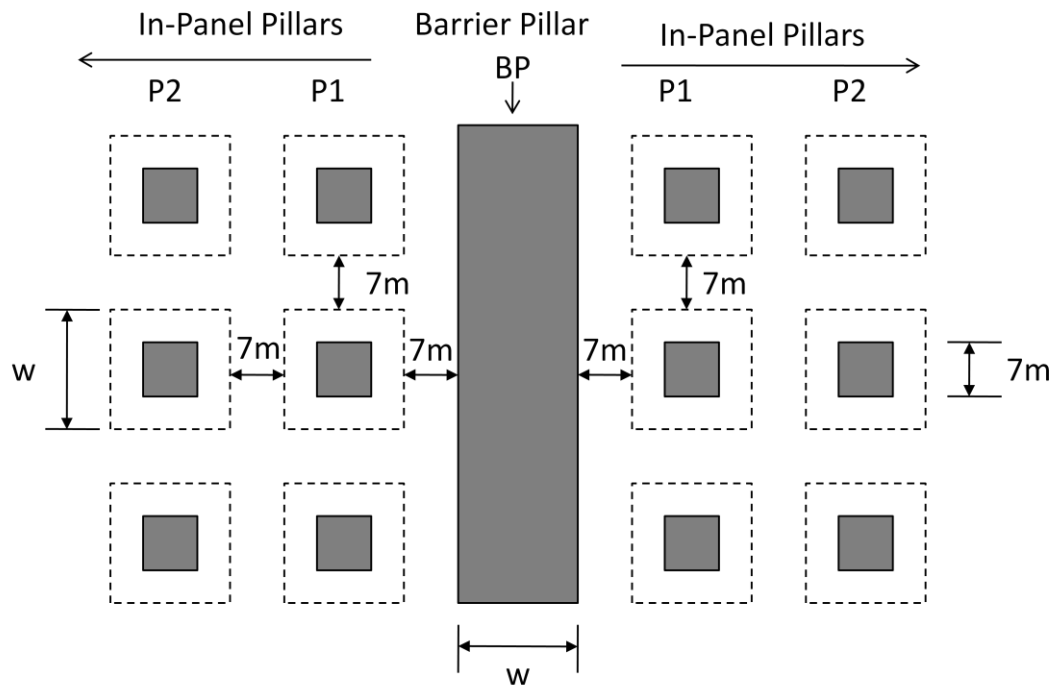


Figure 3.4: Varying in-panel pillars for fixed barrier pillar size and location

Note that, the pillar centre to centre distance (C) remains constant throughout the stages, as a decrease in the pillar width results in an increase in the bord width by the same amount.

(b) Modelling results

• Vertical stress

The vertical stress on both barrier and in-panel pillars increases with a decrease in in-panel pillar widths between fixed barrier pillar positions (Figure 3.5). This agrees well with the tributary area theory (TAT) discussed in Chapter 2 and represented by equation 2.1 in the same chapter.

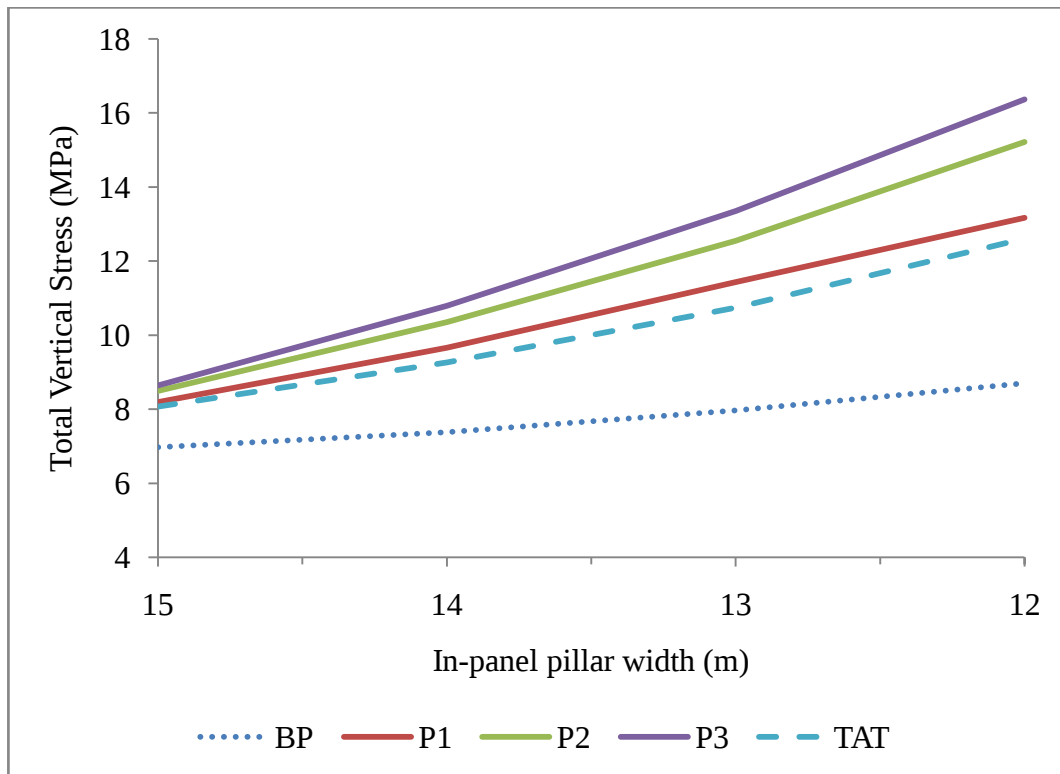


Figure 3.5: Illustration of the effect of decreasing in-panel pillar width on total vertical stress at a depth of 150m

In the figure above, the load represented by TAT is lower than that of the Lamodel and all the pillars have different stresses. The barrier pillars have the lowest vertical stress owing to their fixed width in the model and very long length (length of panel) compared to the in-panel pillars.

In order to represent the variation of the vertical stress with the decrease in the size of in-panel pillars, a stress factor (VSF) has been applied. The VSF used in this analysis is given by:

$$VSF = \frac{\sigma_{pH}}{H}; \text{ Where } \sigma_{pH} \text{ is the average total vertical pillar stress at depth H.}$$

The variation of VSF with in-panel pillar width at various depths shows consistency (Figure 3.6).

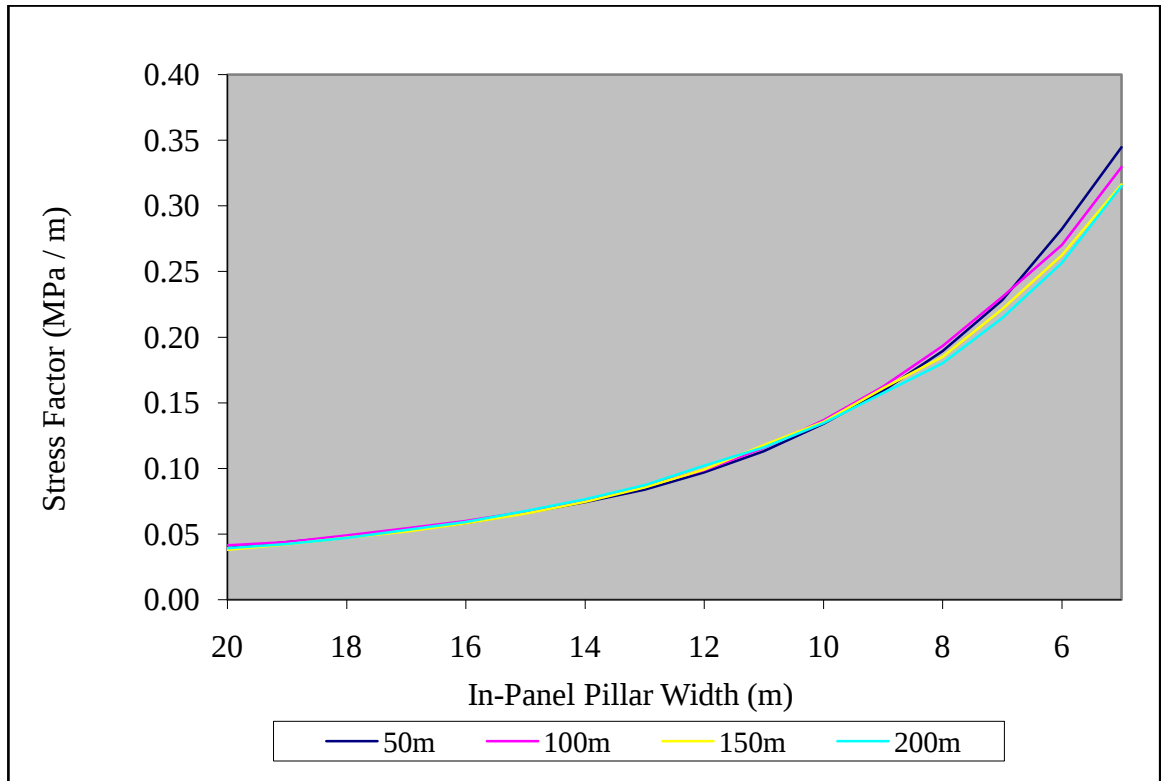


Figure 3.6: In-panel pillar stress factor versus width

It is also realized that pillars closer to the barrier carry less vertical stress than those at the centre of the panel. This is illustrated in figures 3.7 to 3.9.

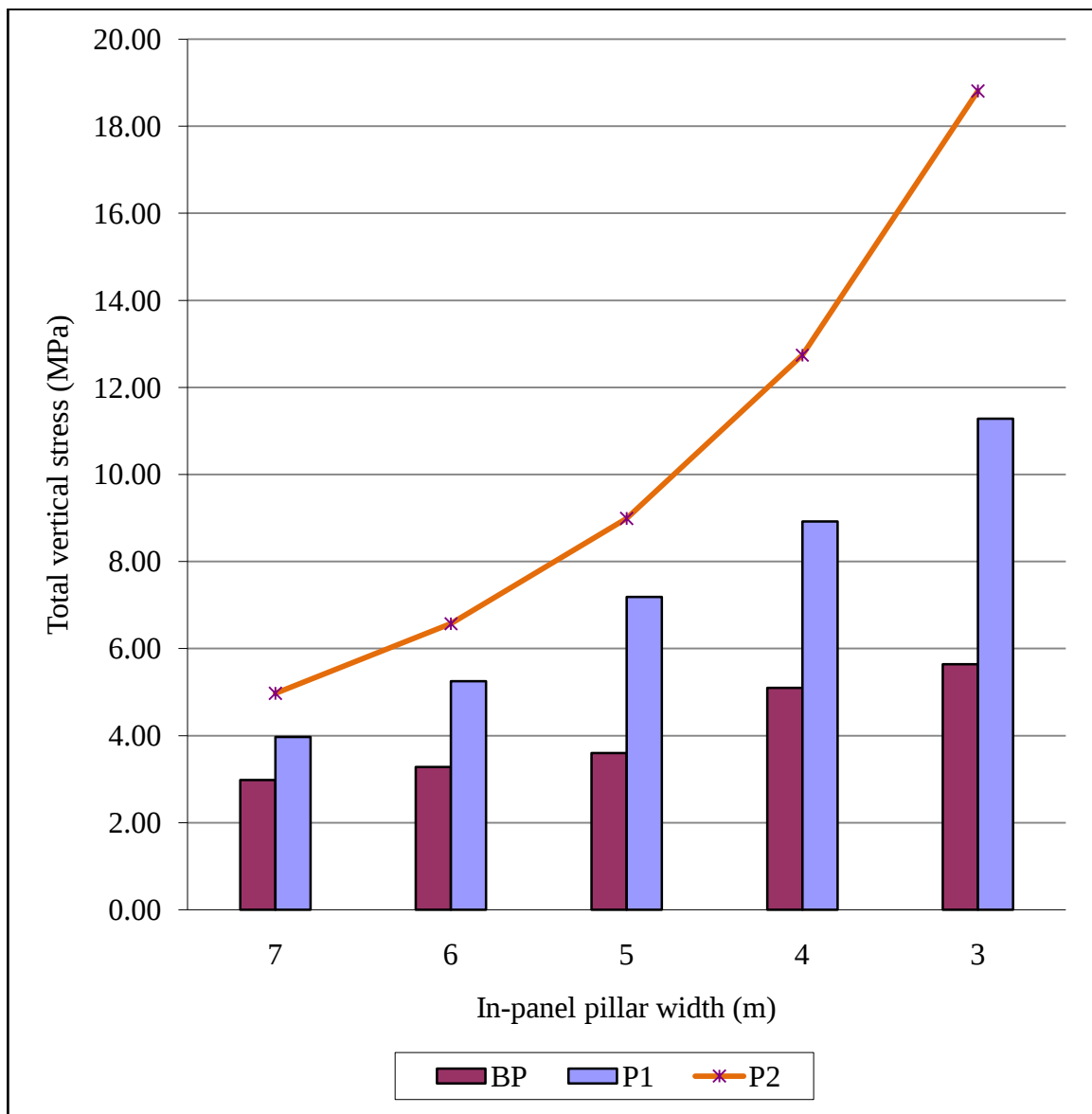
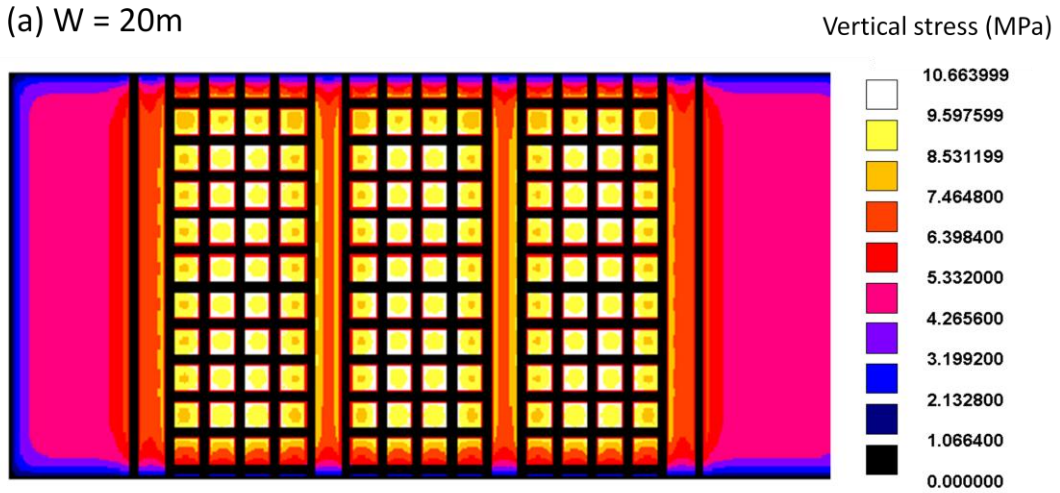


Figure 3.7: Total vertical stress variations with decrease in panel pillar width at 50m depth

(a) $W = 20\text{m}$



(b) $W = 17\text{m}$

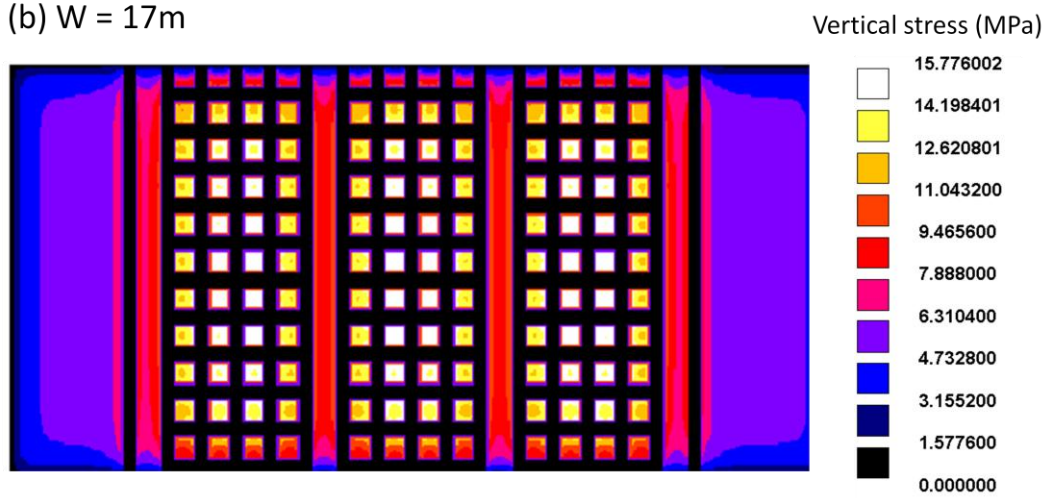


Figure 3.8: Square plot presentations showing the effects of in-panel pillar widths on vertical stress at 200m depth

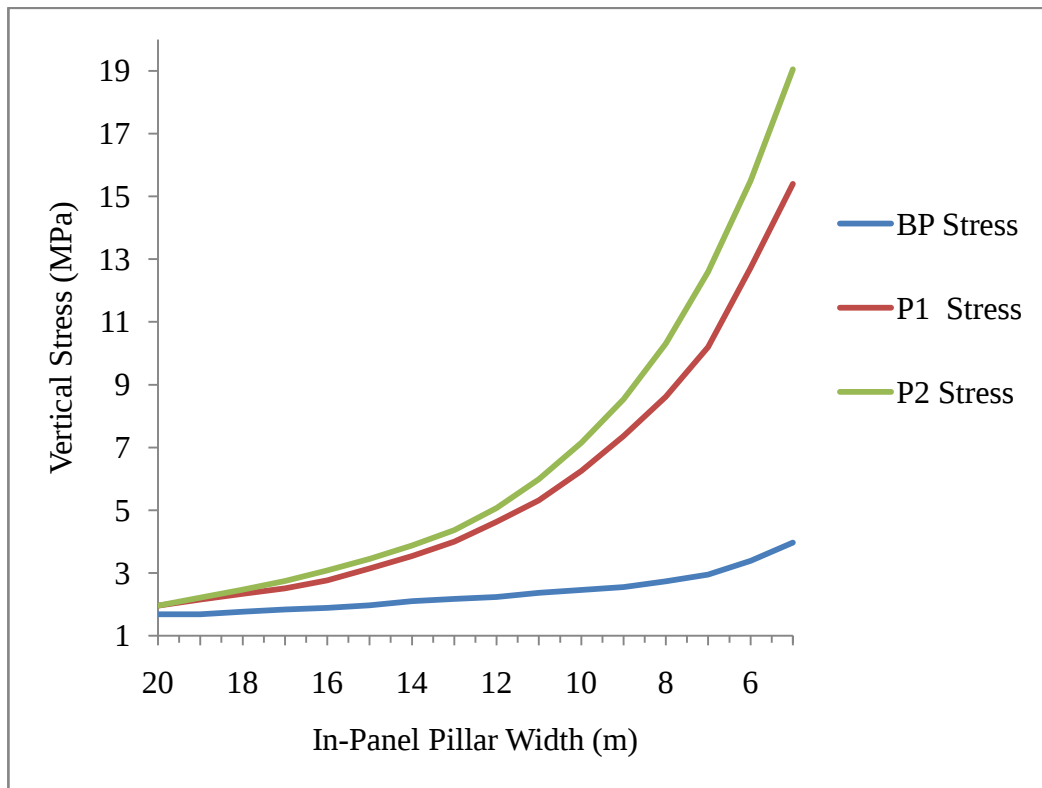


Figure 3.9: BP, P1 and P2 Stress variation with in-panel pillar width at 200m depth

An explanation for the trends shown in figures 3.8 and 3.9 is that, as the in-panel pillars are reduced in size, part of the load that they carried is transferred to the barrier pillars. However, the loads that the in-panel pillars still carry also increase considerably, owing to their smaller sizes.

- **Seam convergence**

Reducing the size of the in-panel pillars increases the bord, and consequently increases seam convergence (Figure 3.10). The bords between BP and P1 pillars have less convergence than those between the in-panel pillars (P1-P2, P2-P3, P3-P4). Convergence increases towards the centre of a panel (Figure 3.11). Bord widths of

more than 10m impact negatively on roof convergence and may not suit local roof control.

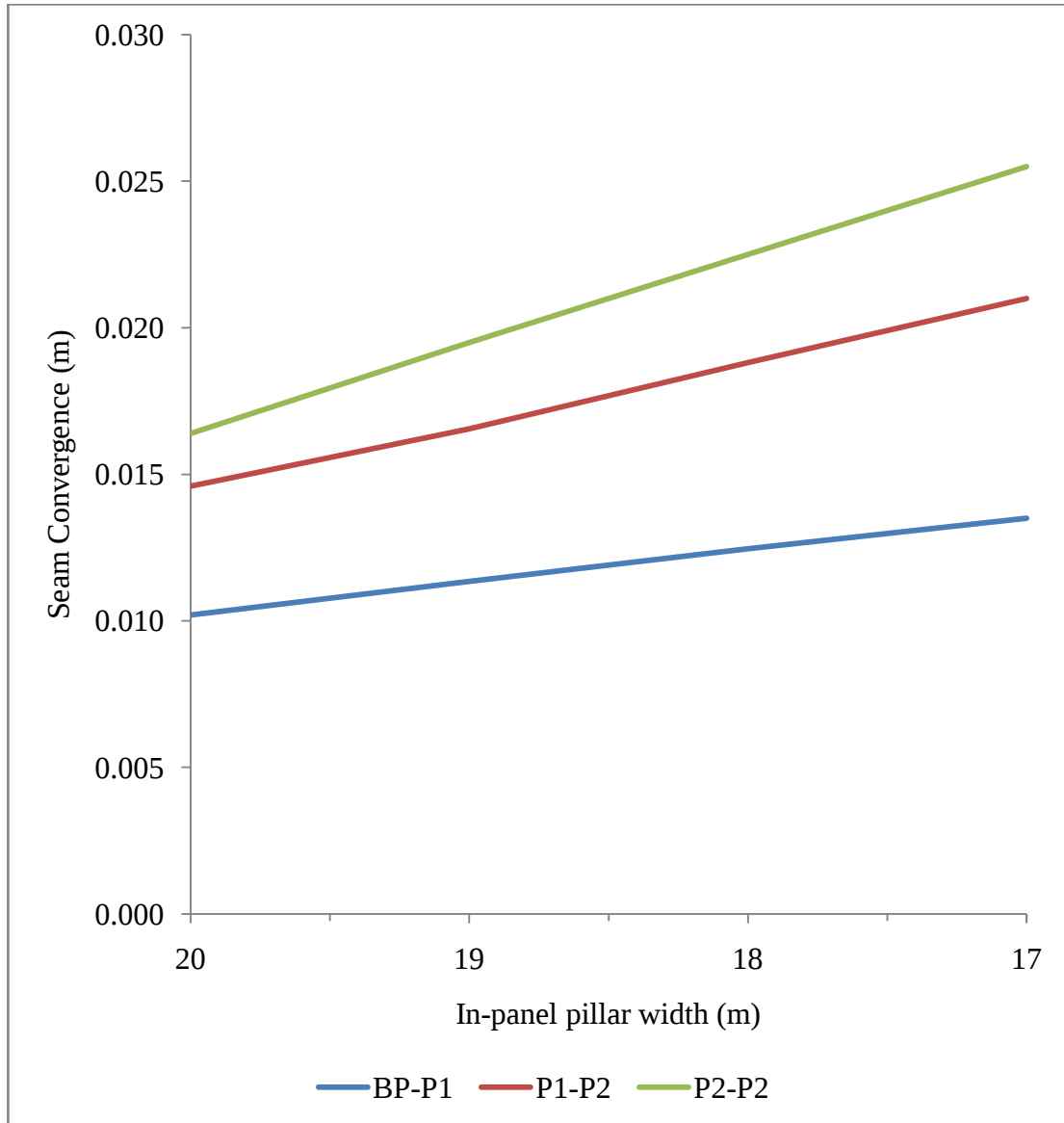


Figure 3.10: Seam convergence at 200m depth

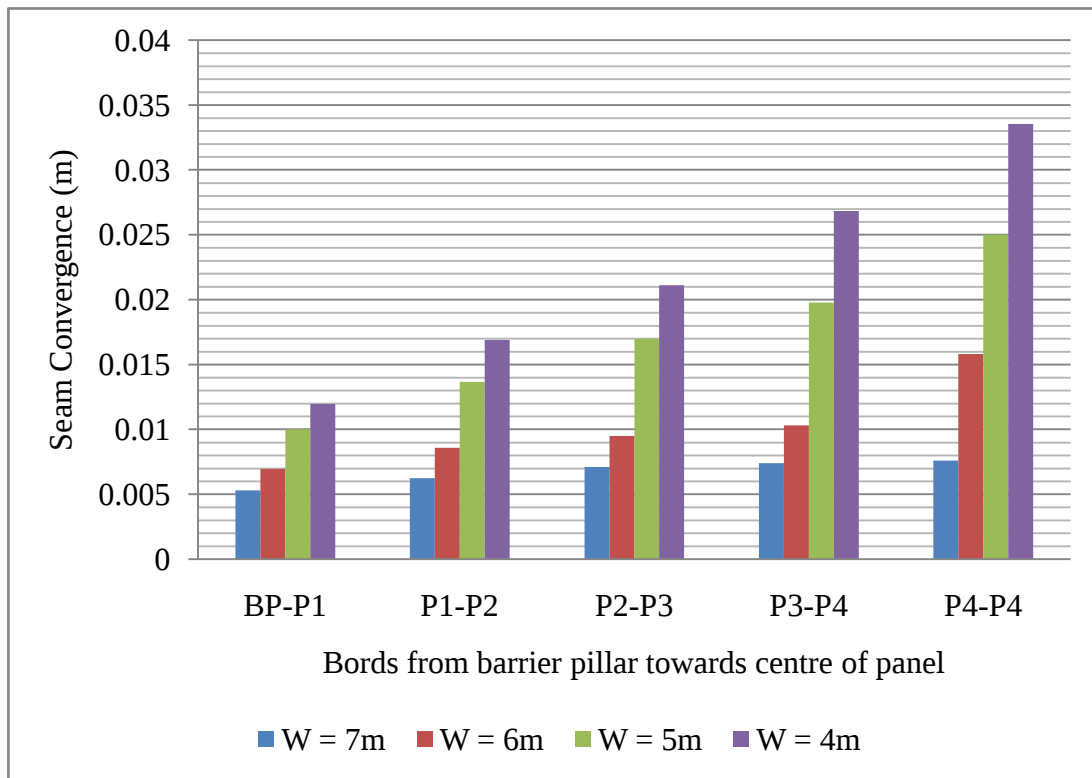


Figure 3.11: Seam convergence across a panel at 50m depth

Convergence is also affected by depth. For the same bord width, the deeper the panel location the higher the convergence (figures 3.10 and 3.11).

- **Pillar strain safety factor**

Figure 3.12 shows the variation of pillar strain safety factor with decrease in in-panel pillar width for the four models at various depths.

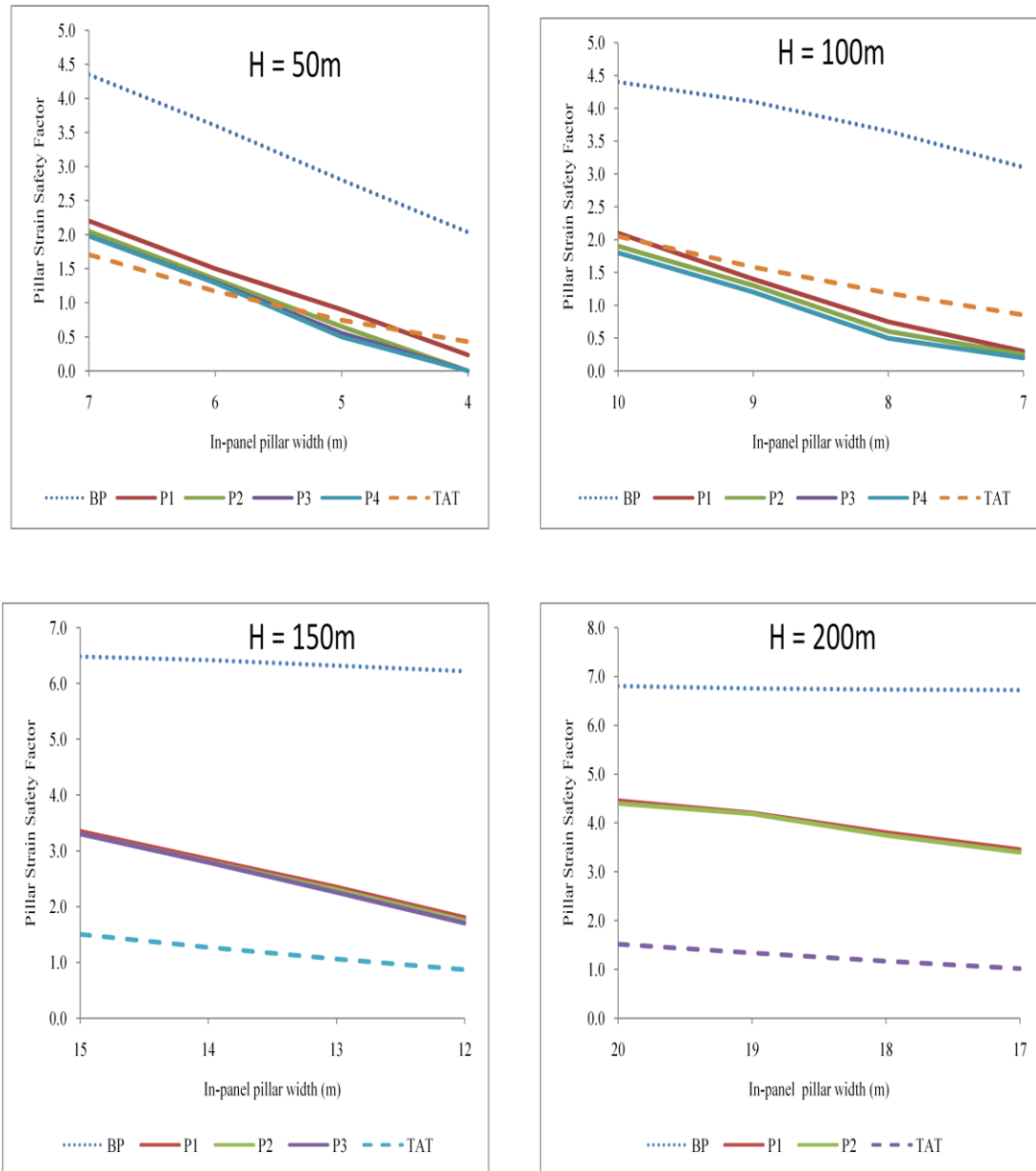


Figure 3.12: Pillar strain safety factor variation with decrease in in-panel width

The above graphs like those of vertical stress show that safety factors decrease with decrease in pillar width. It is also seen that the safety factors are not uniformly distributed across the panels (figure 3.13 below). For the models investigated, the

influence of position on safety factors is more apparent at shallow depths less than 100m. Pillars close to barrier pillars have slightly higher safety factors than the rest of the pillars in the same panel.

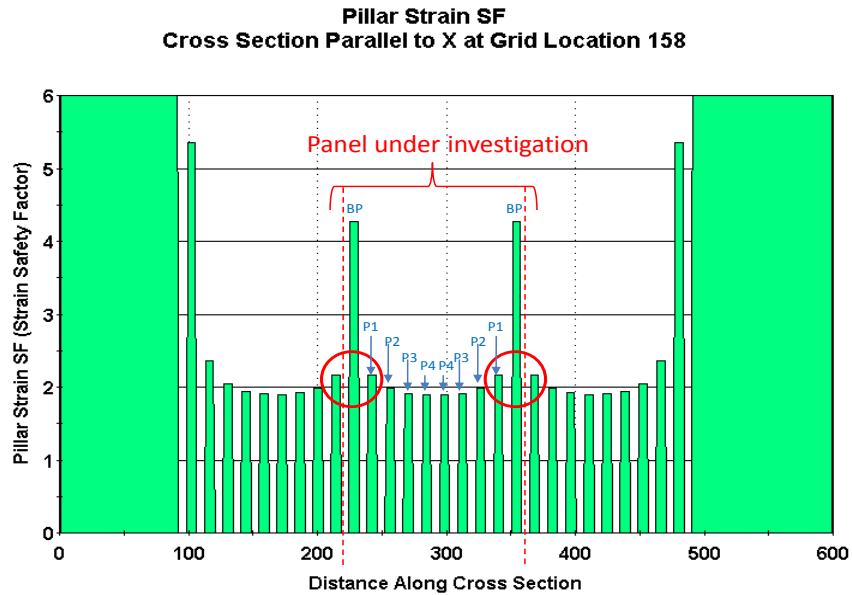


Figure 3.13: Distribution of safety factor across a nine road way panel at 50m depth

(c) Effect on extraction

From equations 2.6 and 2.7, reducing in-panel pillars increases both areal and overall extraction for the models investigated (figures 3.14 and 3.15)

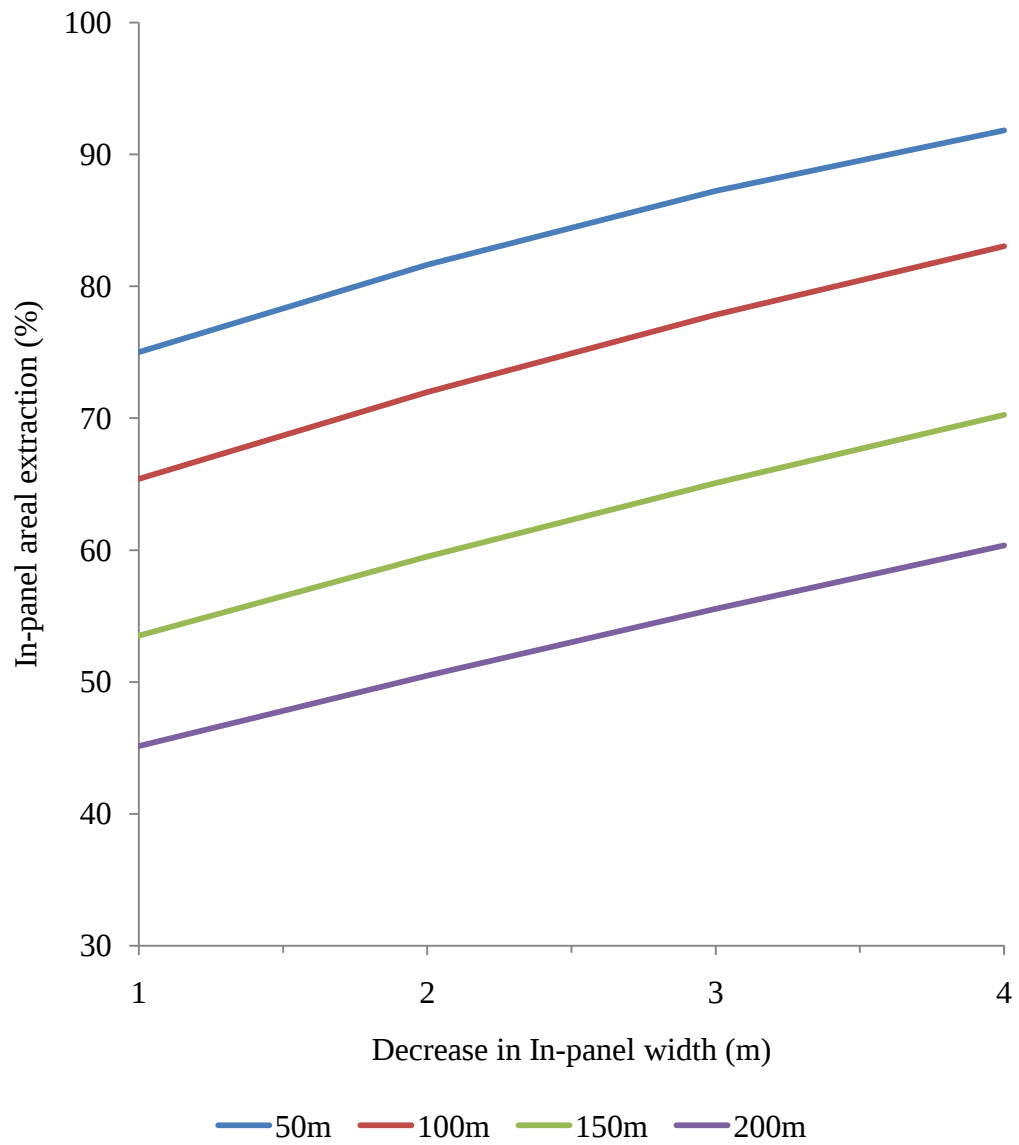


Figure 3.14: Areal extraction with decrease in in-panel pillar width at different depths.

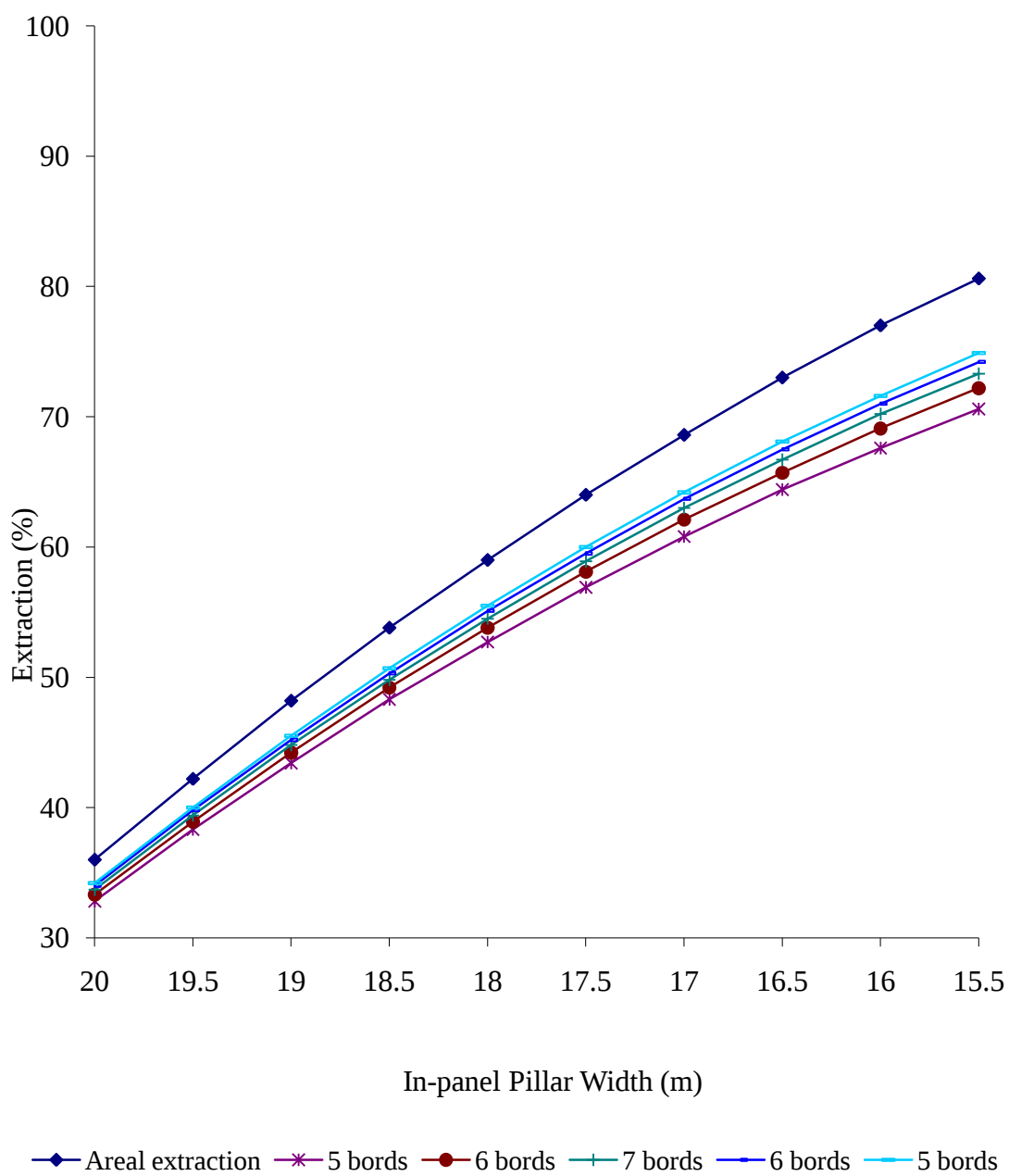


Figure 3.15: Overall extraction with decrease in pillar width at 200m depth.

3.4.3 Varying barrier pillars for fixed in-panel pillar size and location

(a) Model description

In this model, the in-panel pillar and bord widths are kept constant while the barrier pillar width is increased in each one of the stages of the LaModel programme. The same initial design parameters as given earlier have been applied. Figure 3.16 depicts the conceptual model.

The initial width of the barrier pillars has been taken be equal to the width of the in-panel pillar for each panel. This is based on the fact that barrier pillars as wide as adjacent panel pillars are able to resist collapse, as revealed by a study conducted by Esterhuizen (1991).

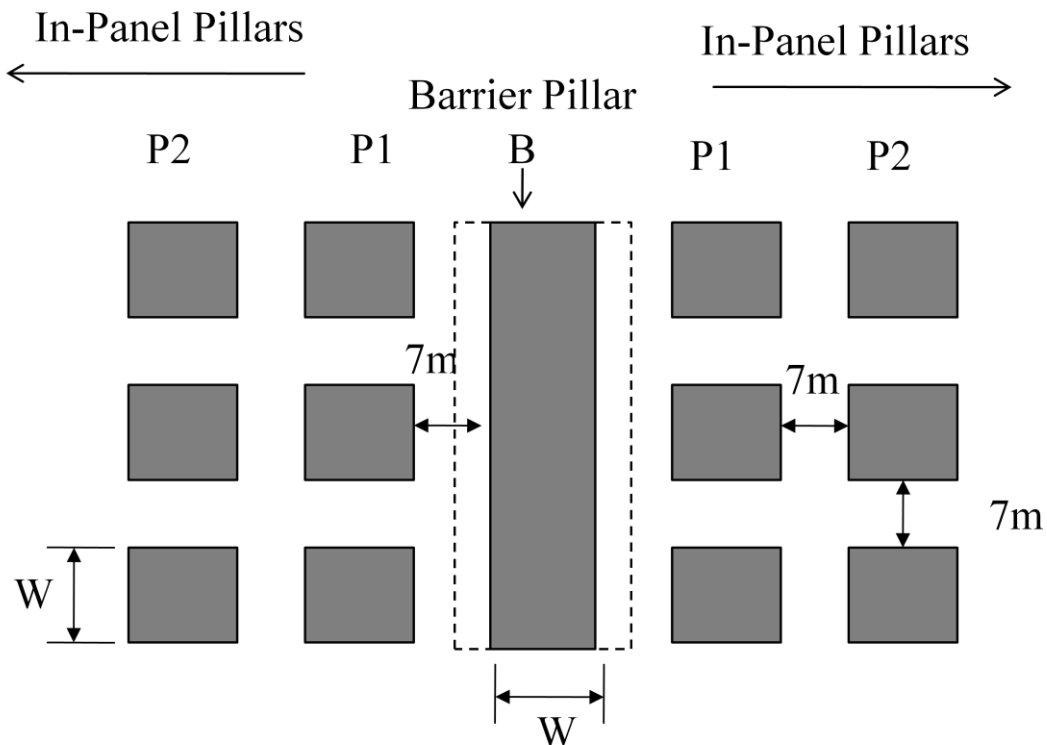


Figure 3.16: Varying barrier pillar size for fixed in-panel pillar sizes

In figure 3.16, the in-panel pillar width w can be 7m, 10m, 15m, or 20m depending on the depth of workings as given in table 3.1.

Increasing barrier pillar width without shifting the in-panel pillars will result in reduced bord widths hence reduced extraction ratio for the mining of P1 pillars. The in-panel pillars may be shifted outwards to maintain the same bord width across the panel.

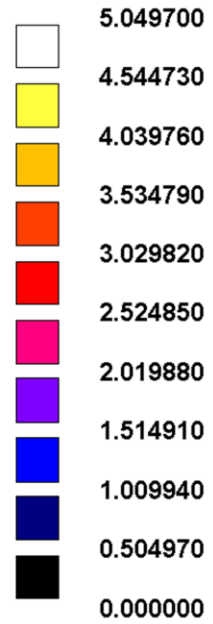
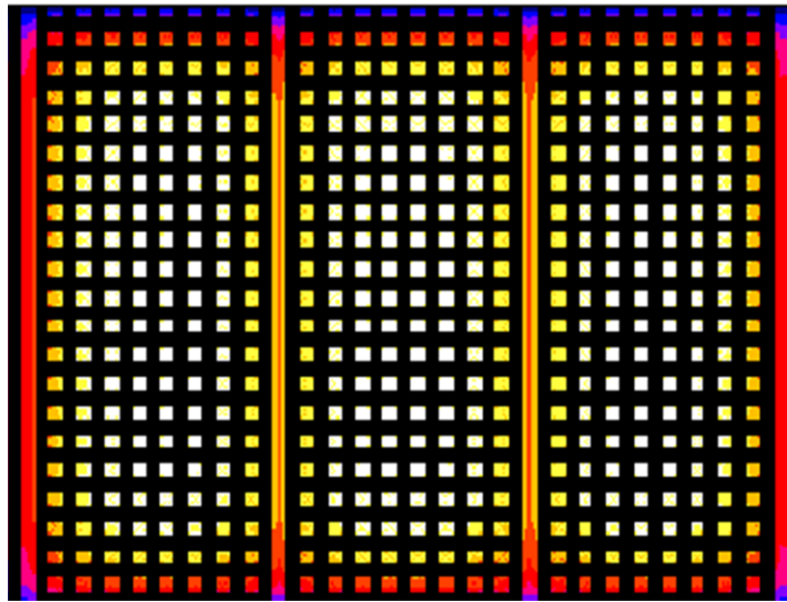
(b) Modelling Results

• Total vertical stress

Modelling has shown that increasing the width of the barrier pillars decreases the total vertical stresses on both in-panel pillars (figure 3.17) and barrier pillars (figure 3.18). From figure 3.18, it can be seen that the stress calculated by TAT is higher than that of the in-panel pillars except for those in the middle of the panel. In general, modelling at various depths has shown that TAT stress is less than that determined by modelling. Figure 3.19 is a coloured square plot of the total vertical stresses on a panel at 50m depth; note P1 pillars have less stress than the other pillars.

As the width of the barrier pillar is increased, stresses across all the pillars decrease up to a certain limit upon which they become almost constant. The decrease is minimal for the central pillars.

(a) BP = 7m



(b) BP = 25m

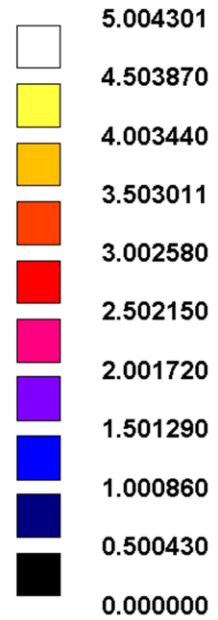
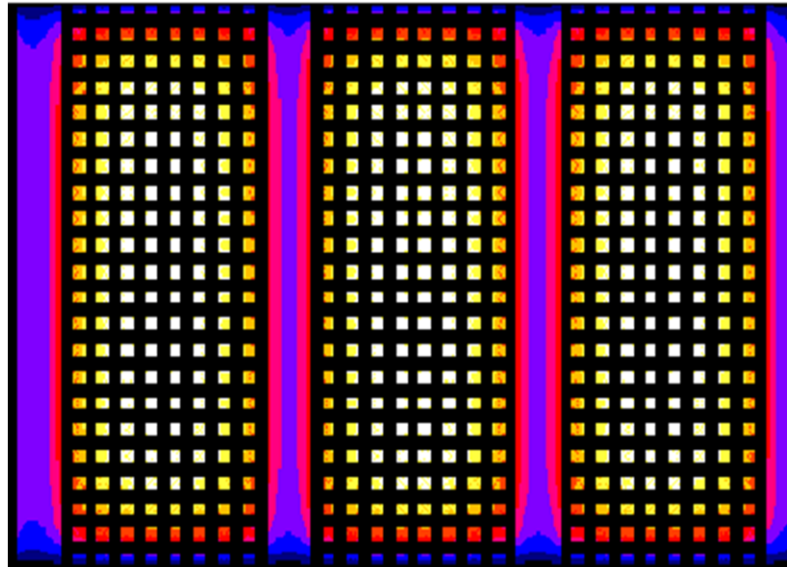


Figure 3.17: Square plot presentation of total vertical stress at 50m depth with barrier pillar width, for (a) the width is 7m and for (b) the width is 25m.

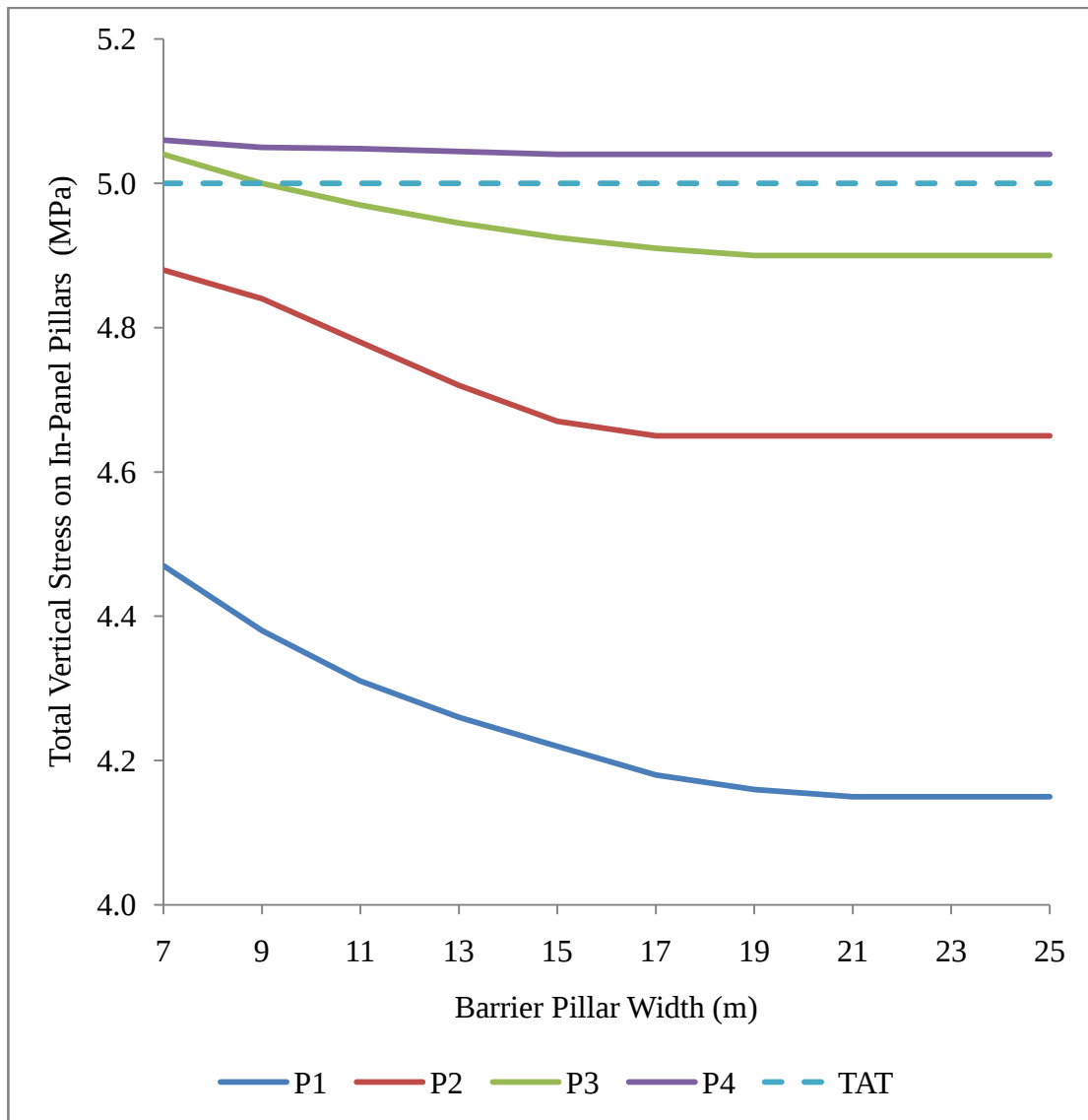


Figure 3.18: Variation of the total vertical stress with increase in barrier pillar width for a panel at 50m depth

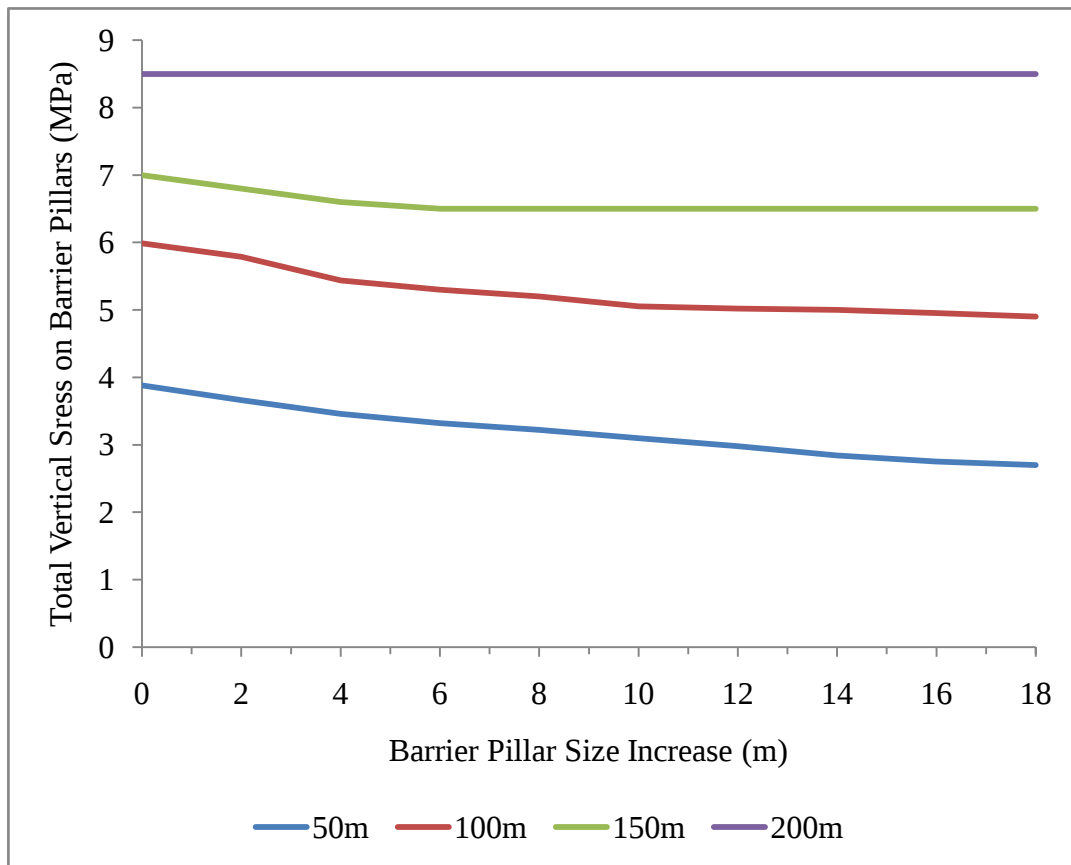


Figure 3.19: Effect of barrier pillar size increase on total vertical stress for panels at different depths

In general, the deeper the panel, the lesser the effect of barrier pillar size on the total vertical stresses on both barrier and in-panel pillars.

- **Seam convergence**

Figure 3.20 below shows the variation of convergence between the barrier pillar and P1 with increase in barrier pillar widths on the four panels at various depths. It is noted that as the width of the barrier pillar is increased, seam convergence decreases. Although convergence becomes higher with depth, its rate of decrease also decreases with depth of mining. This is because the same bord width has been maintained at different depths, the pillars however become larger with depth.

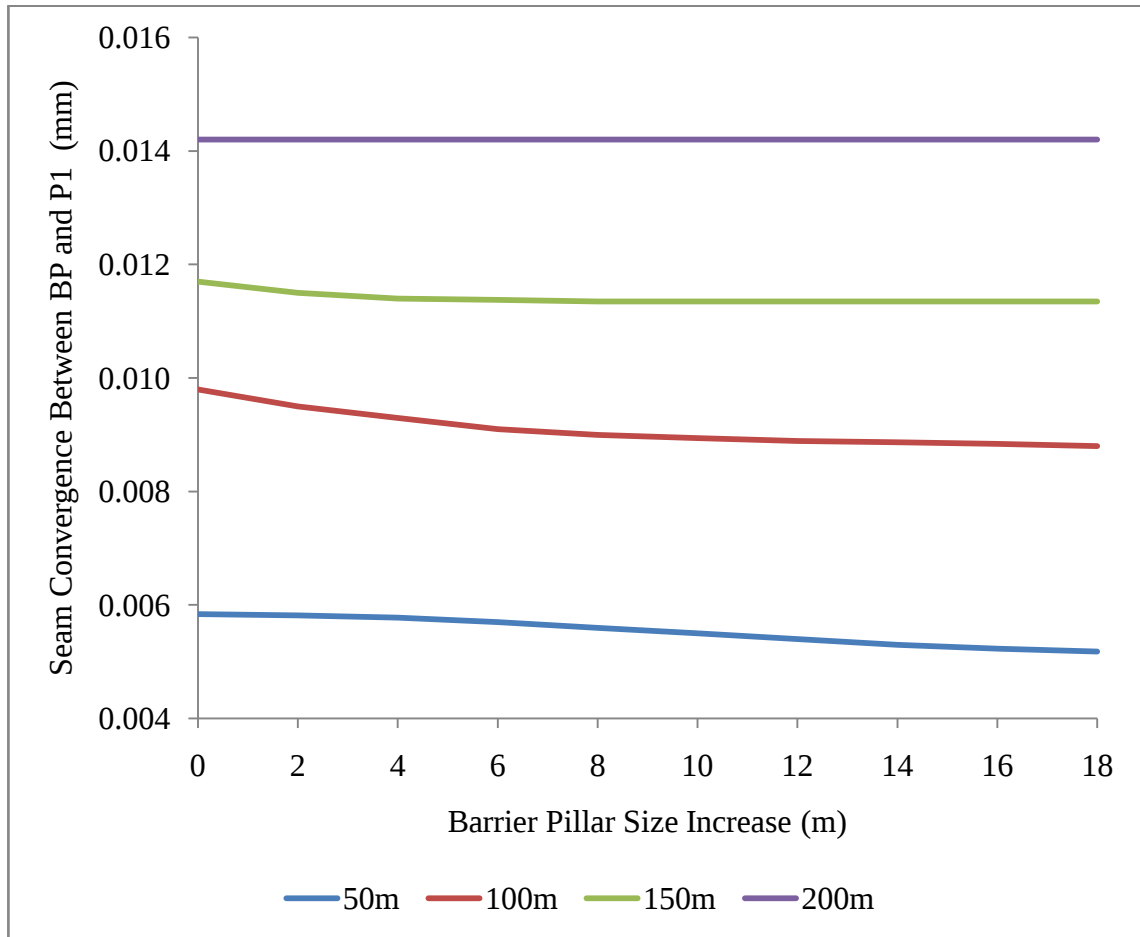


Figure 3.20: Seam convergences versus increase in barrier pillar width at various depths

Convergence in the bords is shown to increase from the bords closer to barrier pillars (bords between BP and P1) to the bords at the centre of panel (Figure 3.21). The bords at the centre of a panel exhibit higher convergence and very little variation in the magnitude of convergence with increased barrier pillar width.

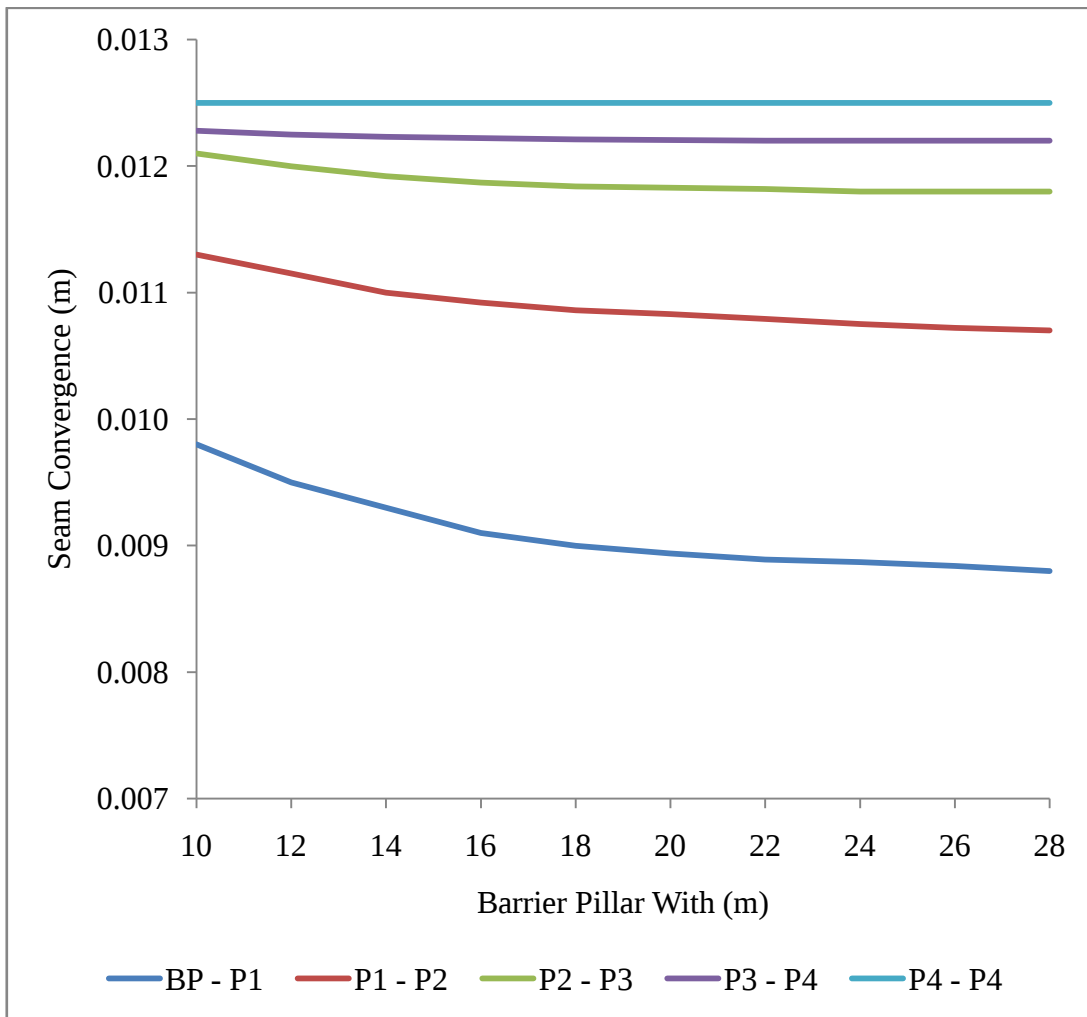
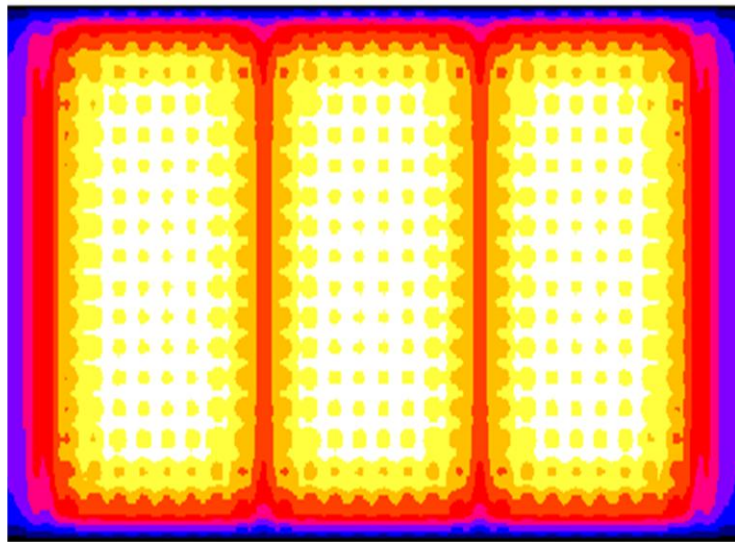


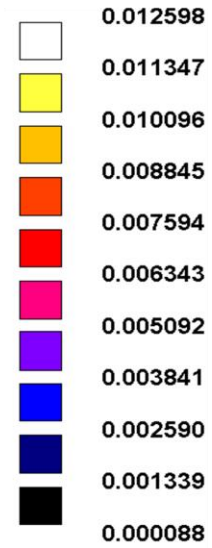
Figure 3.21: Seam convergences between pillars across a nine roadway panel at 100m depth

In figure 3.22 that follows, the barrier pillar width for a panel at 100m depth is increased from (a) 10m to (b) 28m, all the other parameters remain fixed. The results indicate that maximum seam convergence in (b) will be about 0.3% less than that in (a).

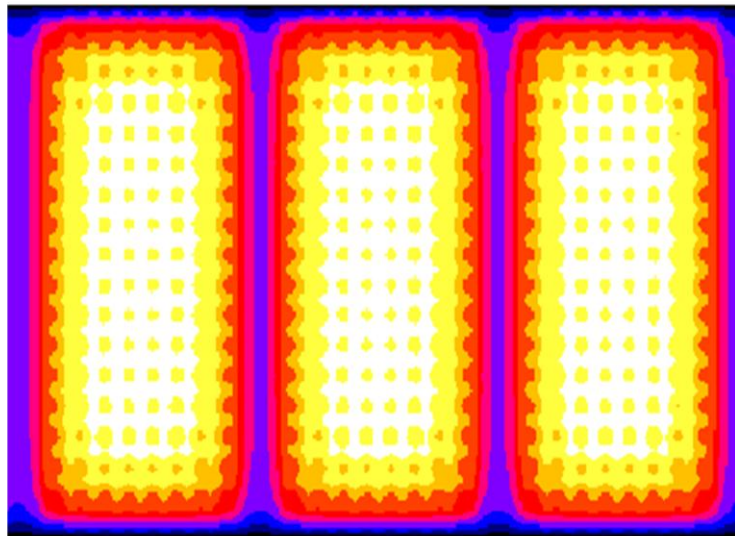
(a) BP = 10m



Seam convergence (m)



(b) BP = 28m



Seam convergence (m)

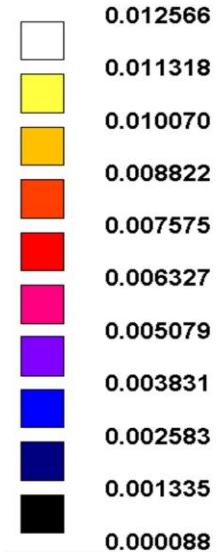


Figure 3.22: Illustration of the effect of barrier pillar size on seam convergence at 100m depth

- **Pillar strain safety factor**

Increasing barrier pillar width increases the pillar strain safety factor for the barrier pillar significantly. The safety factor for P1 pillars increases slightly while the effect on the rest of the in-panel pillars is minimal. This illustrated in figure 3.23 below.

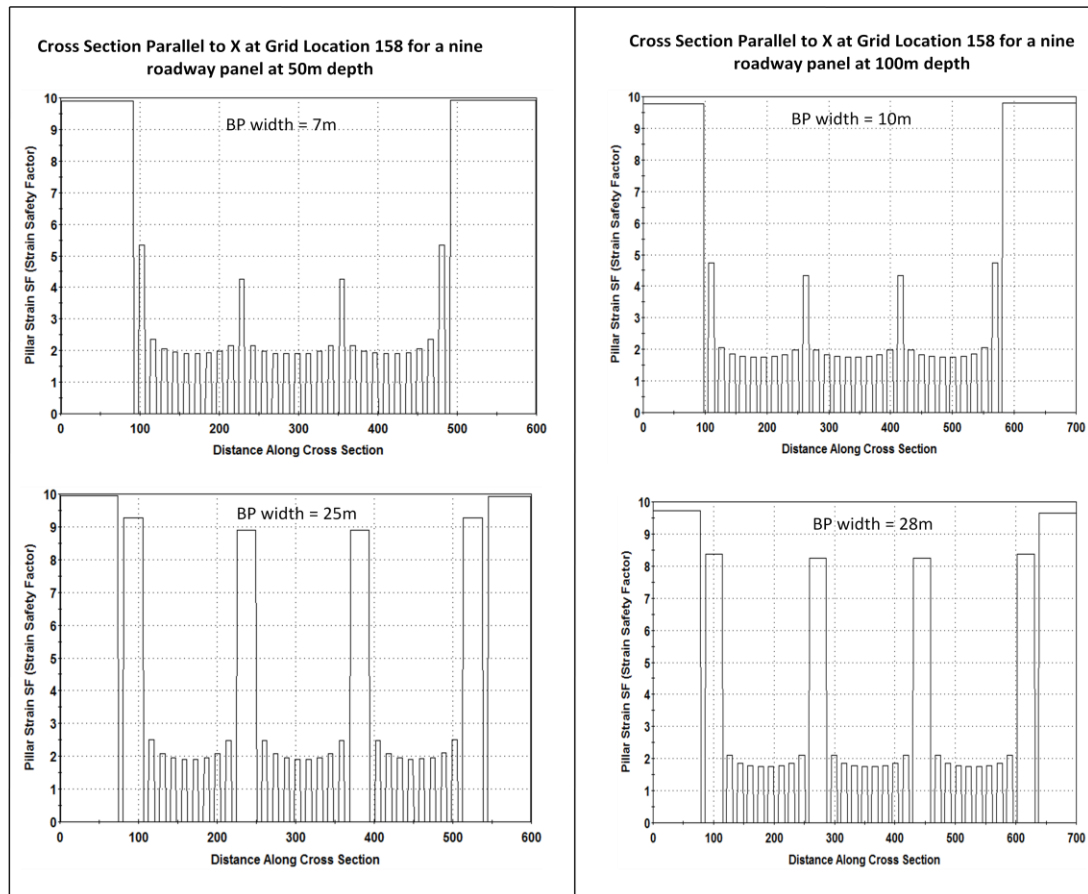


Figure 3.23: Illustration of the effect of increase in barrier pillar width at a depth of (a) 50m and (b) 100m on pillar strain safety factor

(c) Effect on extraction

Since the size of the in-panel pillars and bords for a particular depth remain fixed in the models as the barrier pillar widths are increased, the in-panel areal extraction remains unchanged (equation 2.6). However, the overall extraction that takes into

account the width of barrier pillars is significantly affected (equation 2.7 and figure 3.24).

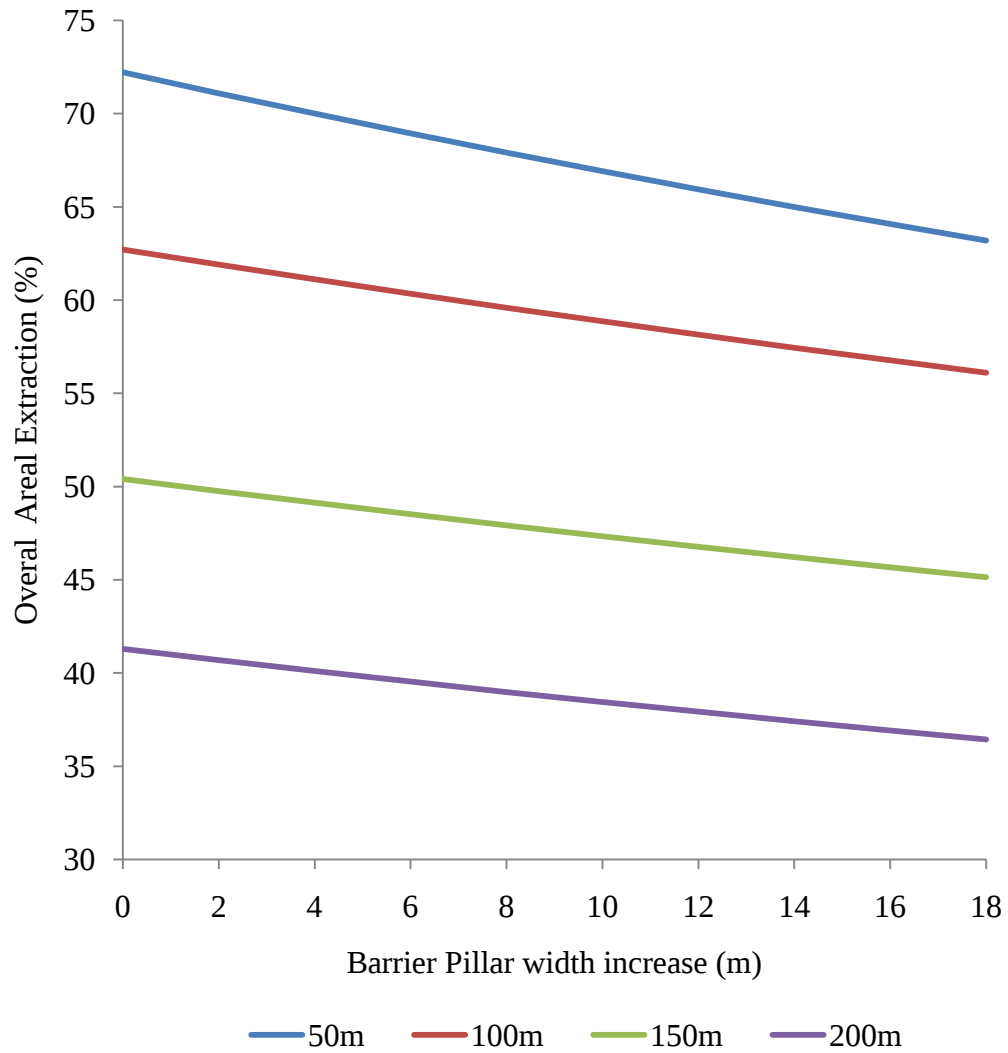


Figure 3.24: Effect of increased barrier pillar width on overall areal extraction at various depths

3.4.4 Varying pillar positions

(a) Model description

In this model the barrier and in-panel pillar widths are kept fixed and the location of the pillars is varied by increasing the bord widths (Figure 3.25). The same model parameters used in model 2 have been applied in this model.

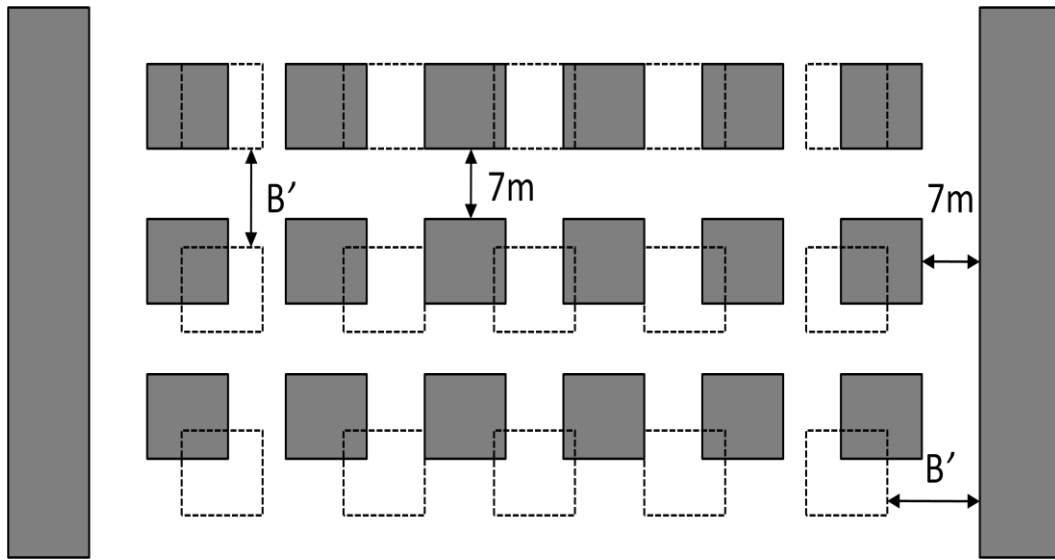


Figure 3.25: Varying bord width for fixed in-panel pillar widths and fixed barrier pillar position

(b) Modelling results

- **Total vertical stress**

As the space between pillars (the bord) is increased, vertical stresses acting on both pillars increases quite significantly (figures 3.26 and 3.27).

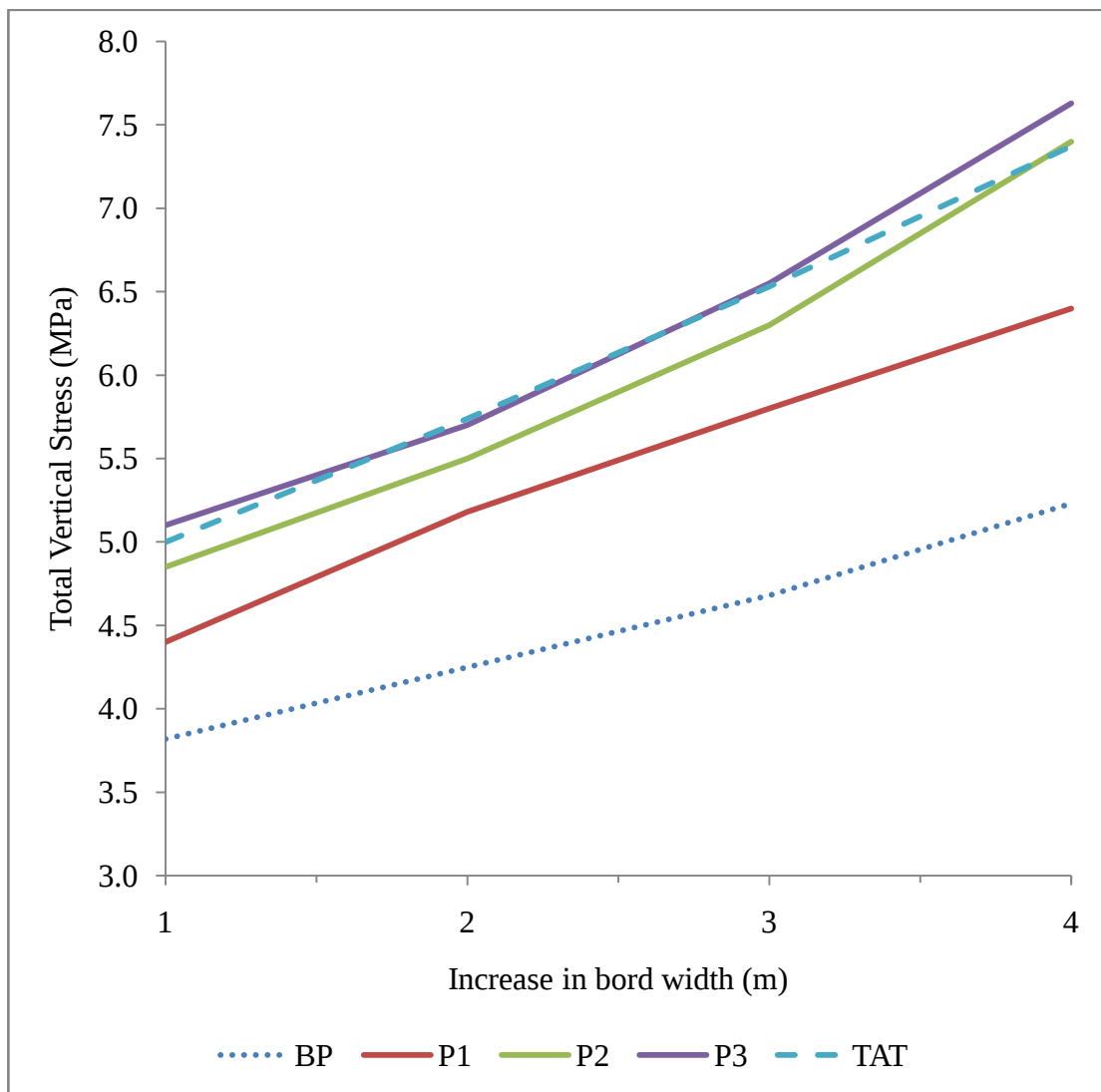


Figure 3.26: Vertical stress on pillars at 50m depth

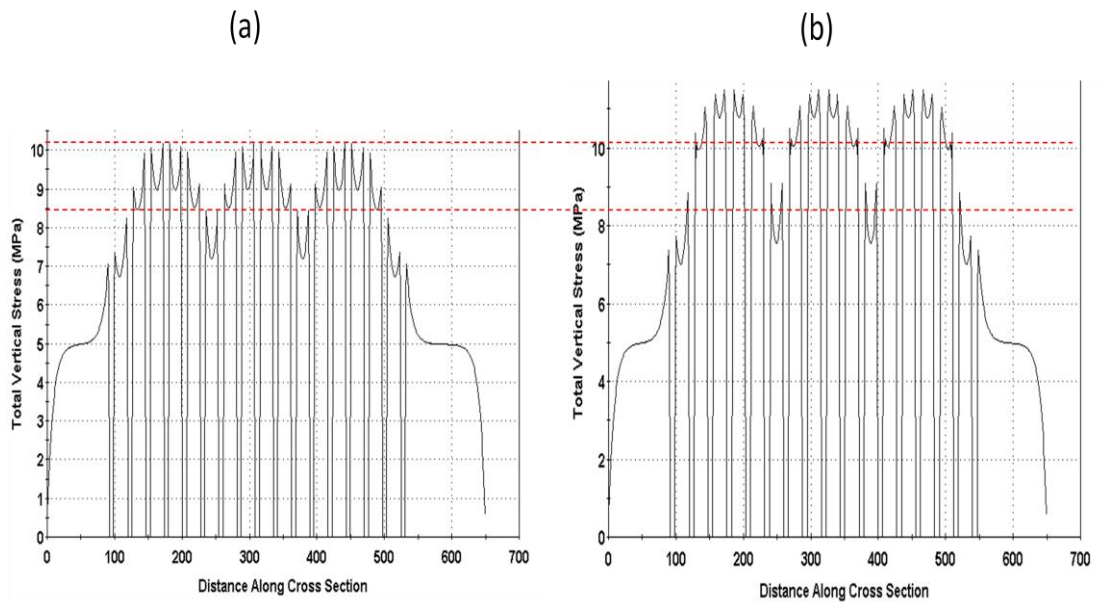


Figure 3.27: Graphical presentation of total vertical stress changes that occur when the bord widths are increased by 1m at 200m depth

- **Seam convergence**

As the roadways are widened, seam convergence increases by an average of about 15% for every metre increase in bord width (figure 3.28).

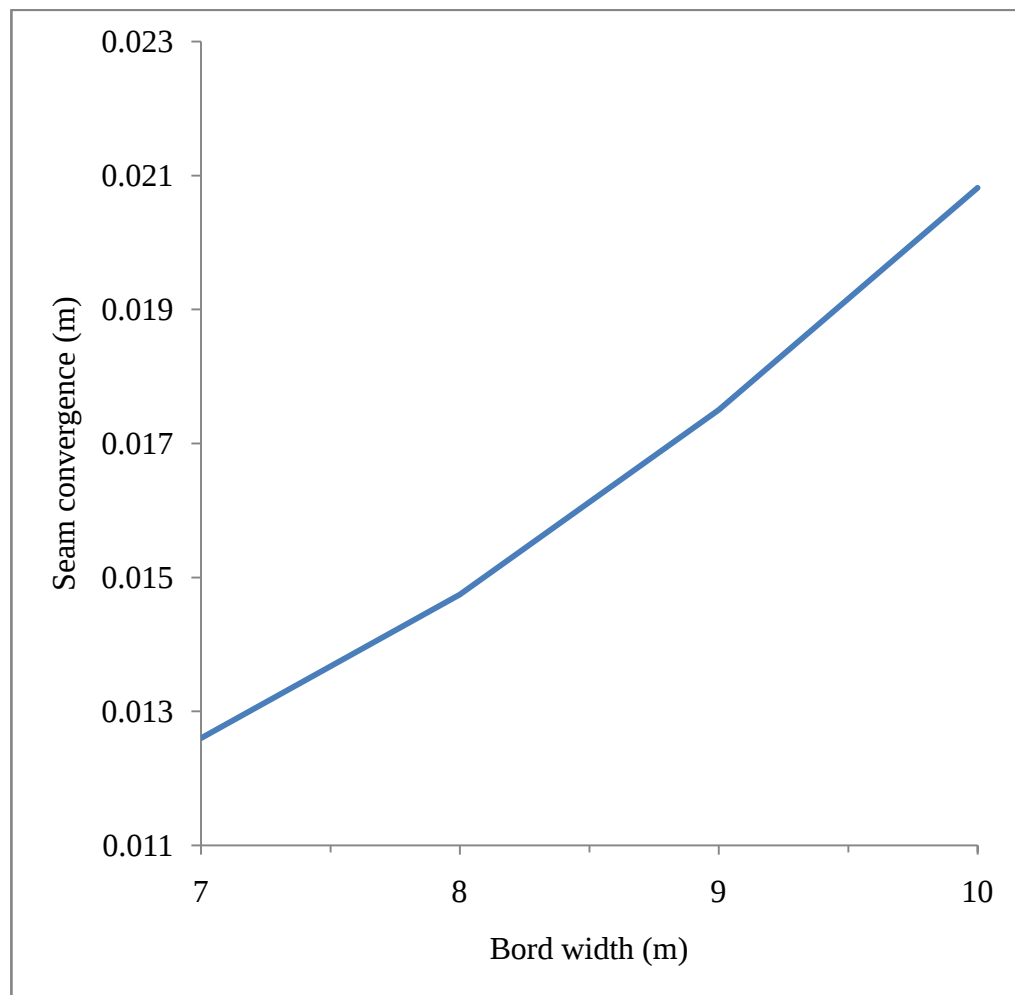


Figure 3.28: Seam convergence versus bord width at 200m depth.

- **Safety factor**

Increasing bord width decreases the Lamodel safety factor (figure 3.29), this is in agreement with the empirical safety factor equation (equation 2.3).

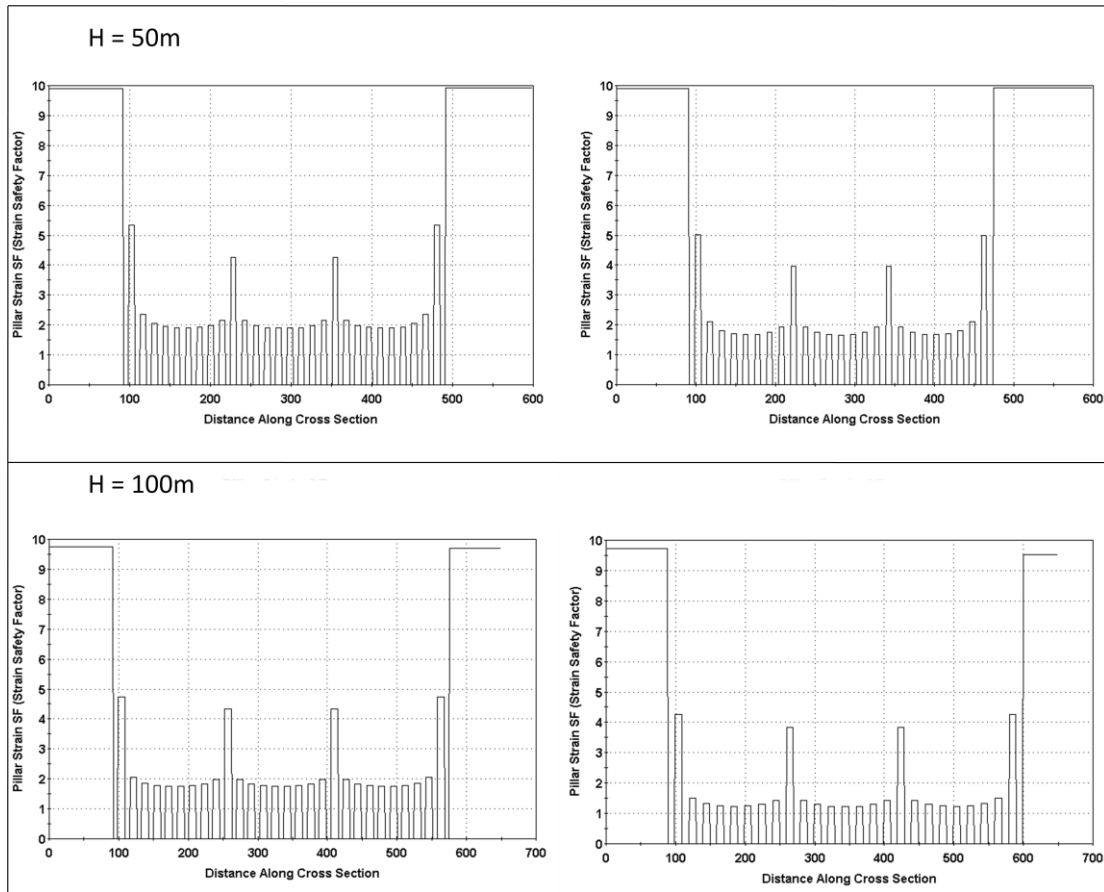


Figure 3.29: Effect of increasing bord width by 1m on pillar safety factor

(c) Effect on extraction

Clearly, an increase in the bord width results in an increase in both areal and overall extraction (figures 3.30 and 3.31).

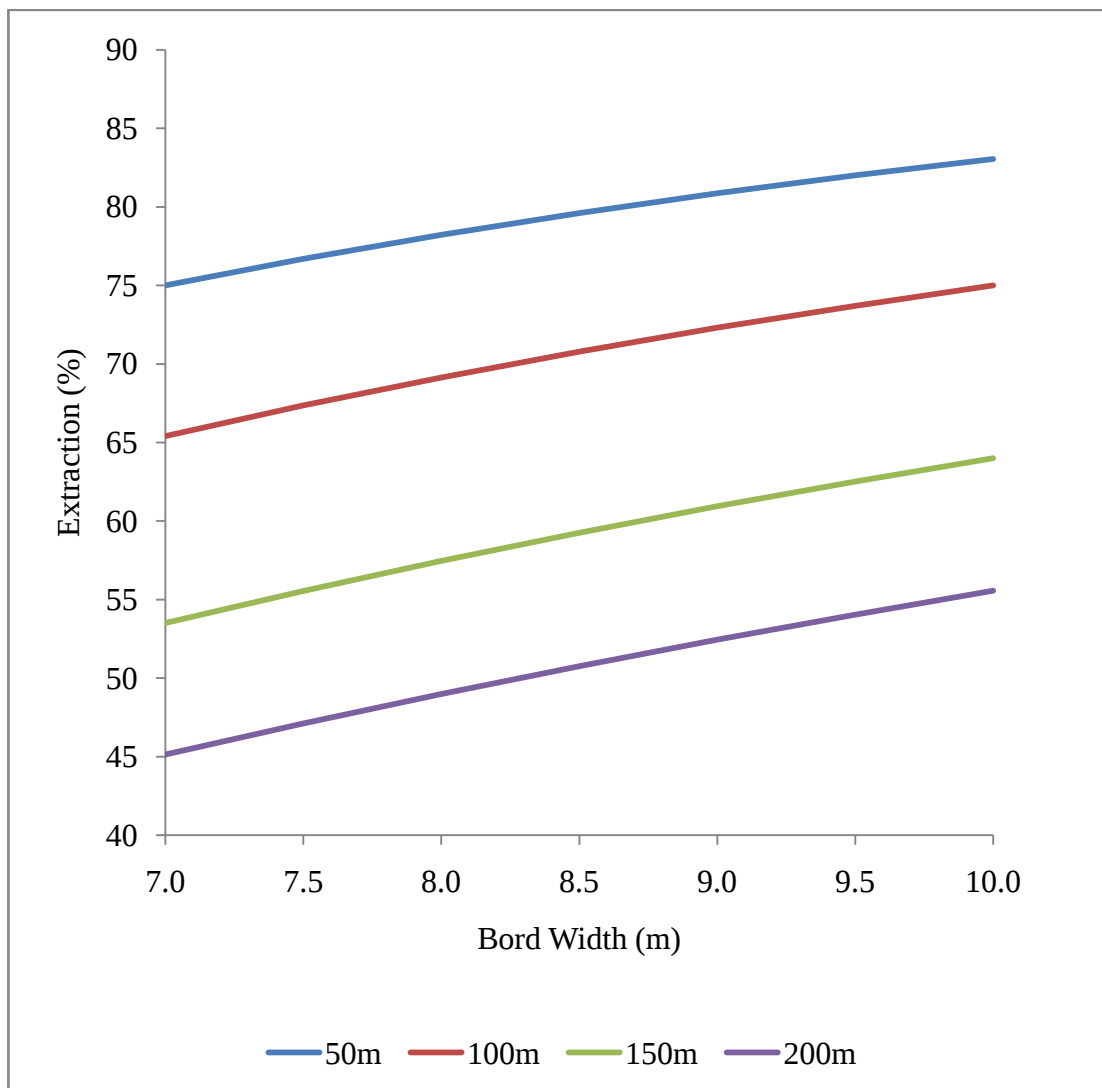


Figure 3.30: Increase in extraction with bord width

3.4.5 Increasing barrier pillar width for reduced in-panel pillar width

This model is aimed at determining by how much the in-panel pillar widths should be reduced for an increased barrier pillar width at the same or better extraction rate. The required in-panel pillar widths will be given by (from equation 2.7):

$$w = \sqrt{\frac{\{C(1-e)[l + (n-1)C + B] - Cl\}}{(n-1)}}$$

In the equation above all the parameters for the model remain fixed except for the barrier pillar width which is being varied. Figure 3.31 illustrates this model.

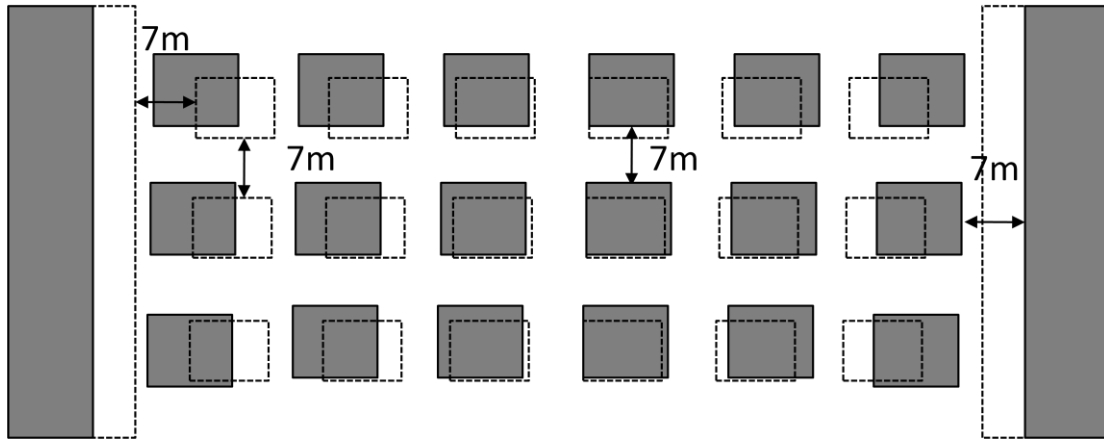


Figure 3.31: Increasing barrier pillars for reduced in panel pillar width

A nine roadway panel at 50m depth, with the in-panel pillar widths of 7m and bords of 7m will have an overall areal extraction of 72.2% (Table 2.1). If this extraction is to be maintained when the barrier pillar width is increased, then the in-panel pillars will have to be resized to maintain the original bord widths. The in-panel pillar areal extraction (75.0%) will however increase (equation 2.6). Figure 3.32 shows the

relationship between in-panel pillar widths and areal extraction with increased barrier pillar widths at fixed overall extraction of 72.2%, 62.7%, 50.4% and 41.3% at depths of 50m, 100m, 150m, and 200m respectively.

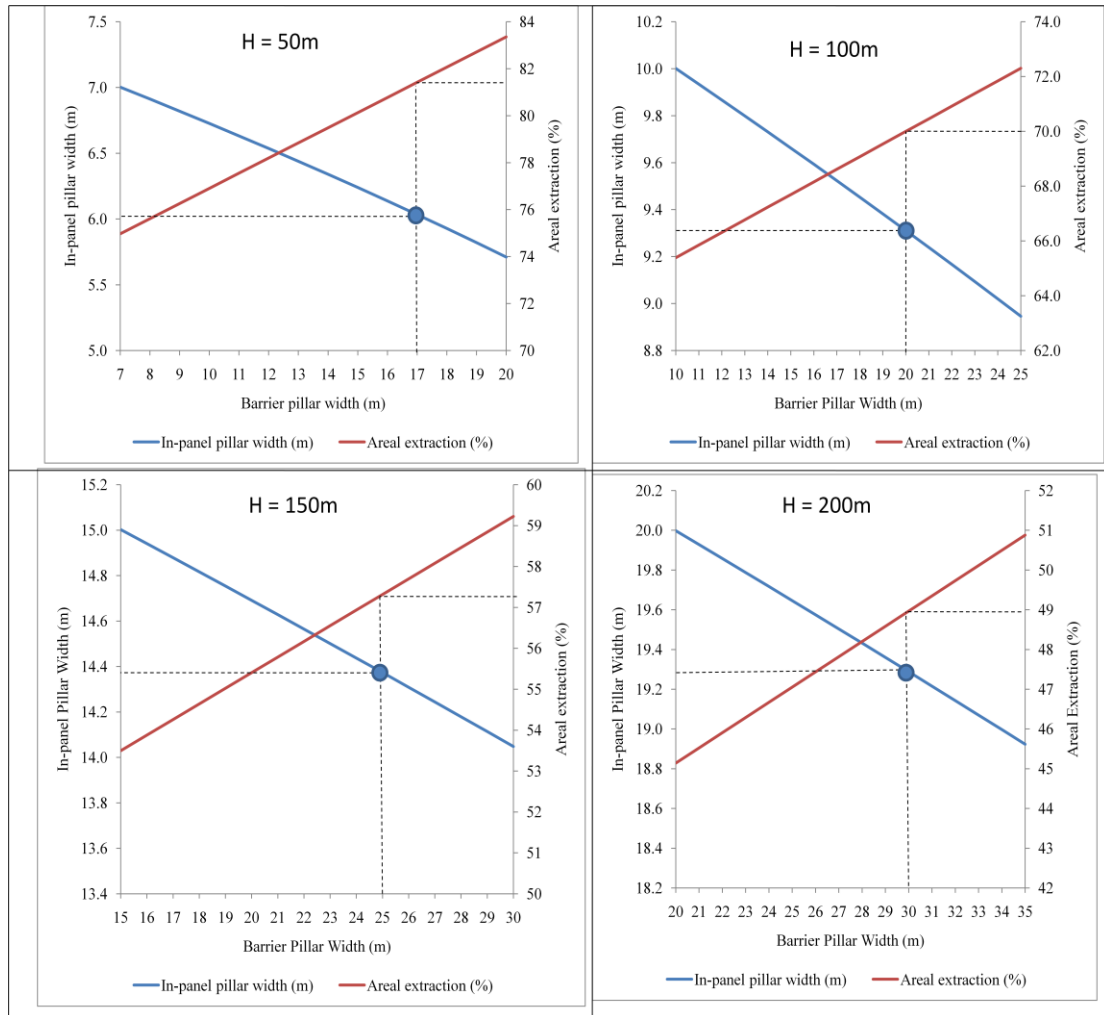


Figure 3.32 Relationship between in-panel pillar widths and pillar areal extraction with increase in BP widths at fixed overall extraction

Table 3.2 that follows shows the increase in areal extraction with increased barrier pillar width for all the panels at different depths as indicated in figure 3.32 above.

Table 3.2: Increase in areal extraction with increased barrier pillar widths at fixed overall extraction

Depth (m)	BP width (m)	Resulting in-panel pillar width (m)	Fixed overall extraction (%)	Increase in areal extraction (%)
50	17	6.0	72.2	6.4
100	20	9.3	62.7	4.6
150	25	14.4	50.4	3.8
200	30	19.3	41.3	3.9

For the panel at 50m depth, if the barrier pillar widths are increased by 10m to 17m, then the in-panel pillars will have to be resized from 7.0m to 6.0m if the same overall extraction is to be maintained. This will increase areal extraction of the in-panel pillars from 75.0% to 81.4%.

A comparison of the resultant vertical stress and safety factor is given in figures 3.33 and 3.34 respectively.

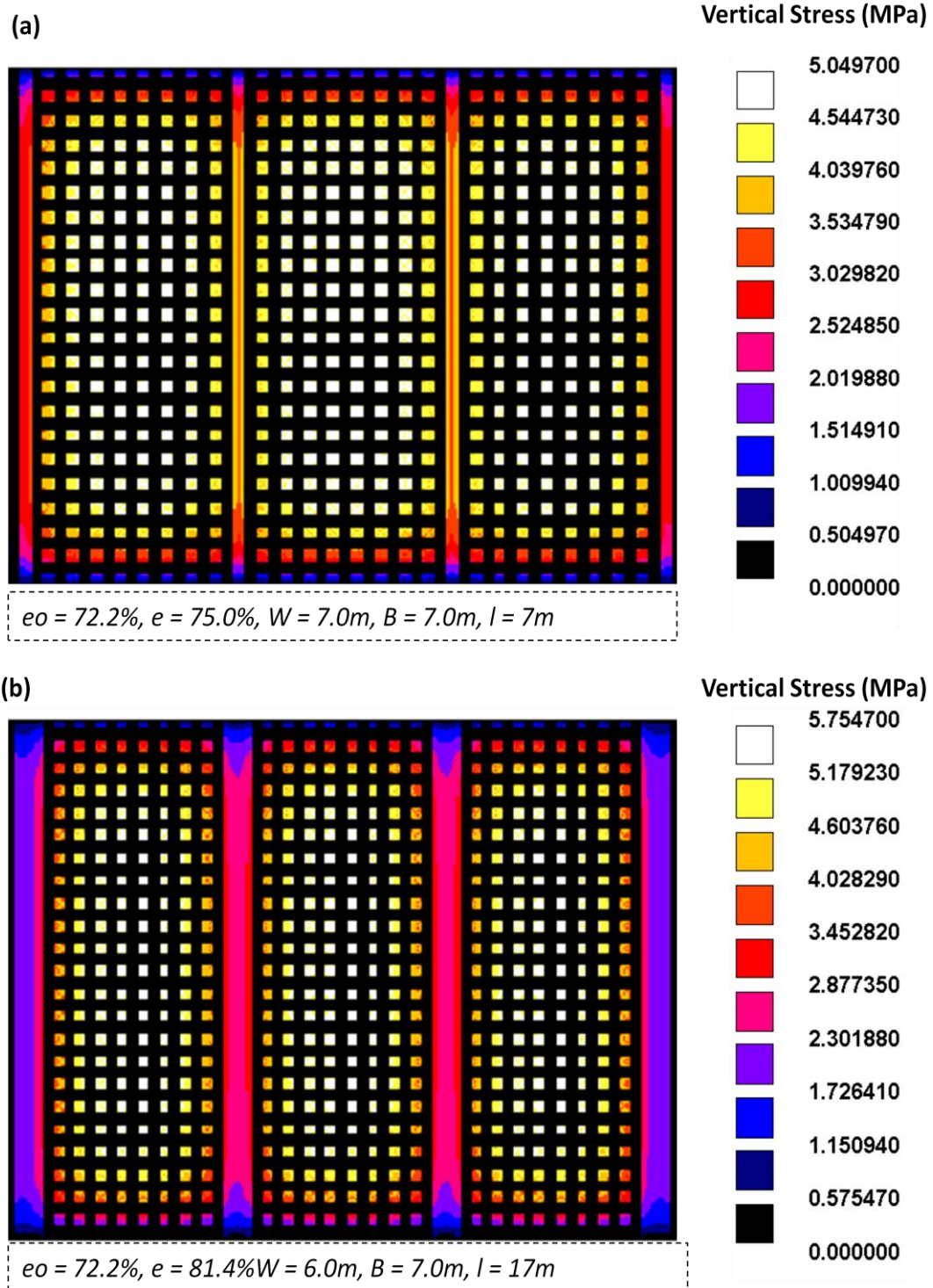


Figure 3.33 Square plot comparison of vertical stress for (a) 7m and (b) 17m barrier pillar widths at 50m depth.

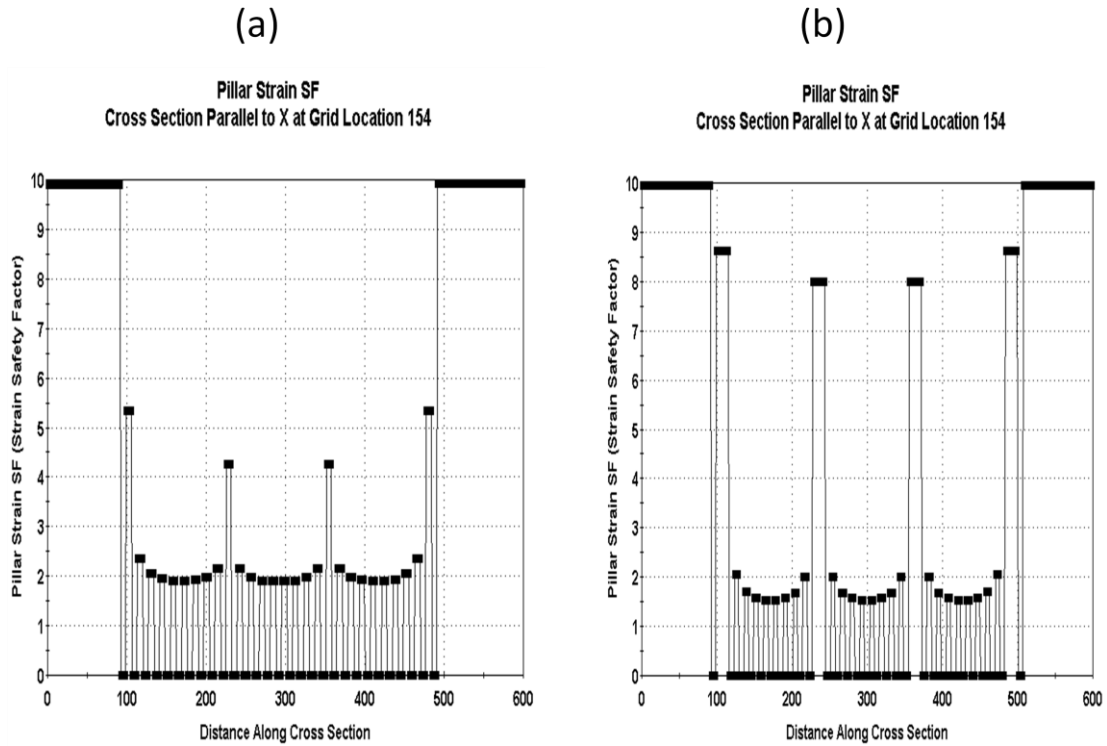


Figure 3.34: Safety factor comparison for (a) 7m and (b) 17m barrier pillar widths for a panel at 50m depth.

While the changes in the vertical stress, safety factor and seam convergence are minimal for pillars close to the barrier pillar, they are quite significant for the pillars in the middle of the panel.

In order to increase overall extraction, the barrier pillar width will have to be reduced. If overall extraction is increased by 1% to 73.3%, then the BP should have a width of 15m and vertical stress will be about 15% higher than that in the initial design.

Figure 3.35 compares safety factors for the panels at different depths, overall extraction being maintained. Note that safety factors for in-panel pillars are reduced while those for barrier pillars increase.

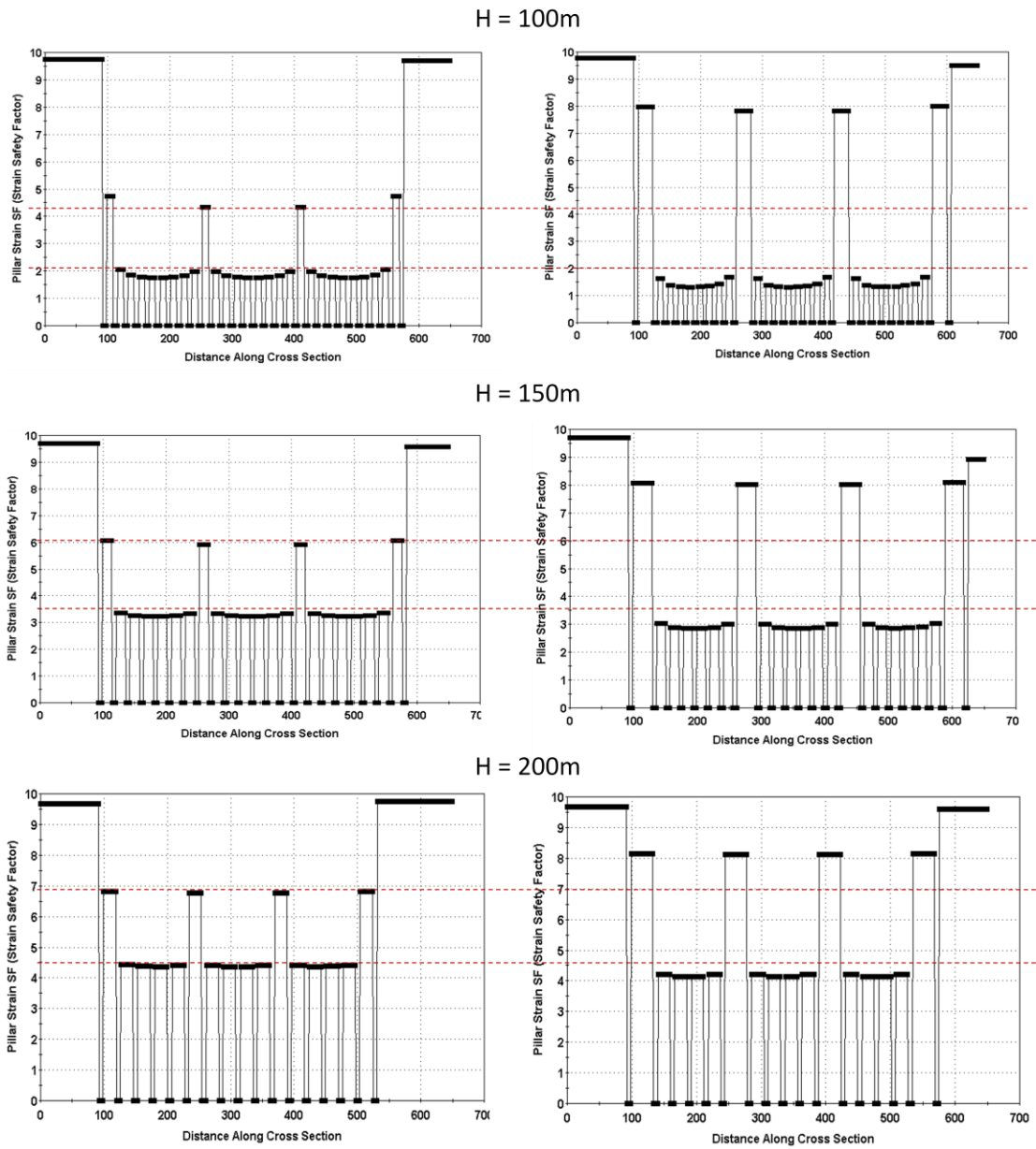


Figure 3.35: Safety factor comparison for panels at different depths

3.5 Summary of Findings

The following trends have been observed from the LaModel investigations:

(a) Varying in-panel pillar sizes for fixed barrier pillar location and sizes:

- TAT stresses are closer to the modelling results for greater in-panel pillar widths and they become higher as the pillars become smaller.
- Both barrier pillar stresses and in-panel pillar stresses generally increase as the widths of in-panel pillars are reduced.
- Barrier pillar stresses are lower than in-panel pillar stresses. They are thus at a higher safety factor.
- In-panel pillars (P1 pillars) next to barrier pillars experience lower stresses than those in the middle of the panel.
- Seam convergence increases towards the centre of the panel for the same bord width and the deeper the coal seam, the higher the convergence.
- Seam convergence increases with increase in bord widths.

(b) Increasing barrier pillar width for fixed in-panel width

- The vertical stresses acting on barrier pillars generally decrease with increase in barrier pillar width.
- The rate of decrease in the stresses acting on barrier pillars decreases as the barrier pillar width is increased.
- The ratio of the vertical stresses acting on in-panel pillars to those acting on barrier pillars increases with increase in barrier pillar width
- Areal extraction remains unchanged, however overall extraction decreases significantly with increase in barrier pillar width.

(c) Increasing bord widths for fixed pillar widths

- Vertical stresses on P1 and P2 pillars increase linearly with the bord width.
- In-panel pillars at the centre of the panel have almost similar stresses to those obtained empirically, and these are higher than for the pillars close to the barrier pillars.
- There is an increase in both areal and overall extraction.

**(d) Increasing barrier pillar width for reduced in-panel pillar widths
(at fixed overall extraction)**

- Vertical stresses on in-panel pillars increase
- Seam convergence at the centre of panel increases
- Safety factors are reduced for in-panel pillars
- Areal extraction increases

3.6 Conclusion

The initial investigation into the loading of various barrier and in-panel pillars for panels at different depth using the Lamodel software package has produced findings that may be useful in the design of bord and pillar layouts. Reducing in-panel pillar widths increases extraction at the expense of stability and increasing barrier pillar widths enhances overall stability of a panel, but has negative consequences on overall extraction. All the models have indicated that pillars close to barrier pillars carry less stress and have higher safety factors than the rest of the pillars in the panel. Addressing these outcomes may lead to the possibility of optimized designs.

Despite the differences in approach for empirical methods (Chapter 2) and the numerical modeling described and investigated in this chapter, the general trends for the vertical stress parameter investigated are in agreement, the only difference being in magnitude.

CHAPTER 4

Underground Investigations

4.1 Introduction

Whilst empirical methods (Chapter 2) assume that pillars in a bord-and-pillar panel experience the same vertical stress, preliminary numerical modelling in Chapter 3 has shown that pillars closer to barrier pillars have less stress upon them. The objective of the practical investigation is to validate the outcome of numerical modelling through underground observation and measurement of pillar scaling at Morupule Colliery, Botswana.

If pillars in a panel are subjected to the same conditions that affect pillar scaling after mining, and the loads acting on the two types of pillars are different, then the amount of scaling on the pillars should also be different.

4.2 Mine Description and Mining Practice

4.2.1 Location and geology

Morupule Colliery is a coal mine located in Palapye, Botswana, and owned and operated by Debswana, a partnership between the government of Botswana and De Beers. Founded in 1973 to supply the nearby Bamangwato Concessions Ltd copper and nickel mine, operations have subsequently expanded considerably to supply a number of regional power plants and industries, especially the nearby Morupule Power Station.

The coalfield is composed of four main seams (figure 4.1), namely Serowe, Lotsane, No. 2 and Morupule. The Morupule Seam, where current mining activities are taking place, has a thickness of between 8 and 11 metres, and is located at a depth to floor of between 80 and 100 metres below surface. Production over a recent 7-year stretch averaged 877,000 tons per year. Overall coalfield reserves are estimated at 5 billion tons of coal.

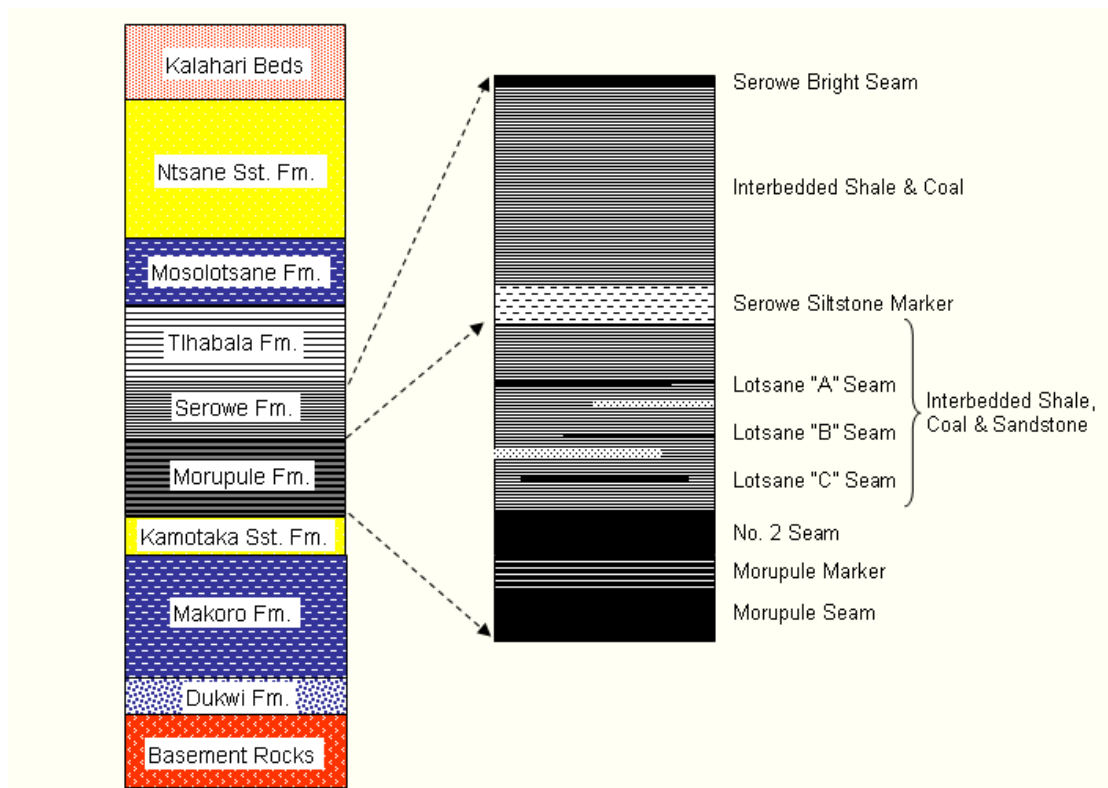


Figure 4.1: Stratigraphic column for Morupule Colliery

4.2.2 Mining method

Morupule Colliery is currently extracting the Morupule Seam at a mining height of 4.2 metres by bord-and-pillar mining utilizing continuous miners. In former years drill and blast mining was employed. The average pillar width is approximately 13.5 m square and bord widths are 6.5 m (20 m centres). Panels, which contain eight

pillars, are separated from adjacent panels with 20-35 m wide barrier pillars. Panel spans between barriers vary between 170 and 190 m.

Current production is targeted at one million tonnes per annum and is expected to increase to four million tonnes on a planned expansion programme.

4.3 Morupule Pillar Stability and Pillar Scaling

The coal strength at Morupule has been reported to be variable, more cleated and weaker than the South African Highveld coal seams (Munsamy, 2007). To compensate for the perceived “weaker” coal a conservative approach was applied to the pillar design which has resulted in the pillars being designed to a safety factor of 1.8 or higher.

Despite higher safety factors being applied, a major problem that is affecting Morupule pillar stability is the deterioration of pillars, resulting in pillar scaling and roof falls. It is noted that progressive pillar scaling increases the bord width, which increases the chances of roof failure. Moreover, scaling also affects the stability of the pillar itself since strength is directly proportional to the width to height ratio of the pillar (Chapter 1).

According to Salamon et al (1998), the intensity of scaling may depend on environmental factors, the composition of the coal and stresses applied to the pillar. If the load on a pillar is increased due to a reduction of pillar width emanating from scaling, the magnitude of scaling should also increase.

4.4 Pillar Scaling Investigations

4.4.1 Area under investigation

The area under investigation is a panel mined more than 30 years ago by the drill and blast method and connects the entire underground workings with surface. The panel measures 195.5m in width and 1 175m in length. The original design entailed the use of square pillars measuring 12m, a mining height of 3.0m and a bord width of 6.0m, at a mining depth of 80m. Figure 4.2 shows the underground layout for Morupule Colliery and the area investigated.

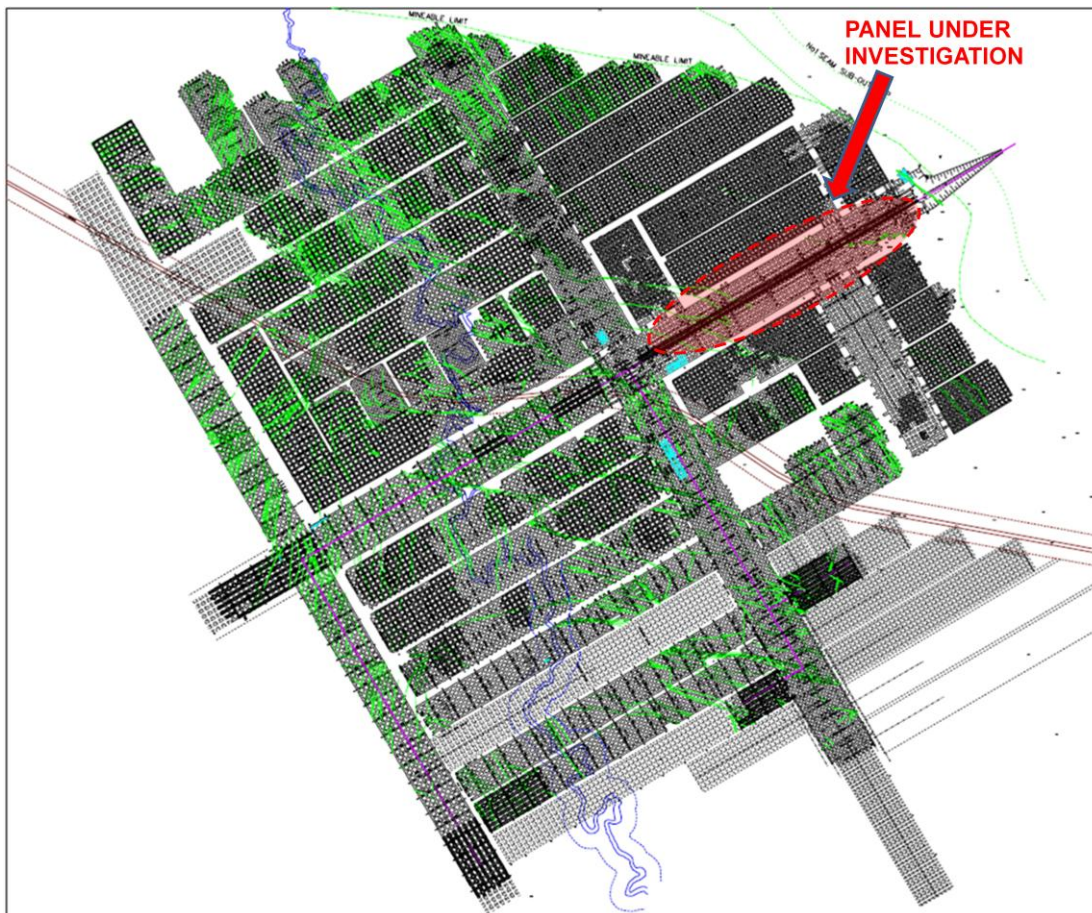


Figure 4.2: Illustration of the mine layout and panel under investigation (Morupule Colliery, 2007)

There are more than 600 pillars in the panel, arranged in tens per row. Of these pillars 200 were selected for input into the database. The pillars were selected based on their accessibility to conduct measurements right around the pillar.

The investigation process adopted assumes that the weakening of pillars is due entirely to a reduction in pillar width induced by scaling.

4.4.2 Measurements

In order to determine the intensity of pillar scaling across the panel, measurements of the bords and pillar heights were taken. A total of 1400 bord width measurements were taken around the 200 pillars selected using an electronic distance measuring instrument. Figure 4.3 illustrates the positions of measurements for the bords.

Measurements were taken at the mid height of pillar; three readings were taken at each side of the pillar giving 12 measurements around each pillar (figures 4.3 and 4.4). No preferential scaling directions were noted. Mining heights were measured at the intersections of the drives and cross-cuts, and an average of 3.0m was determined.

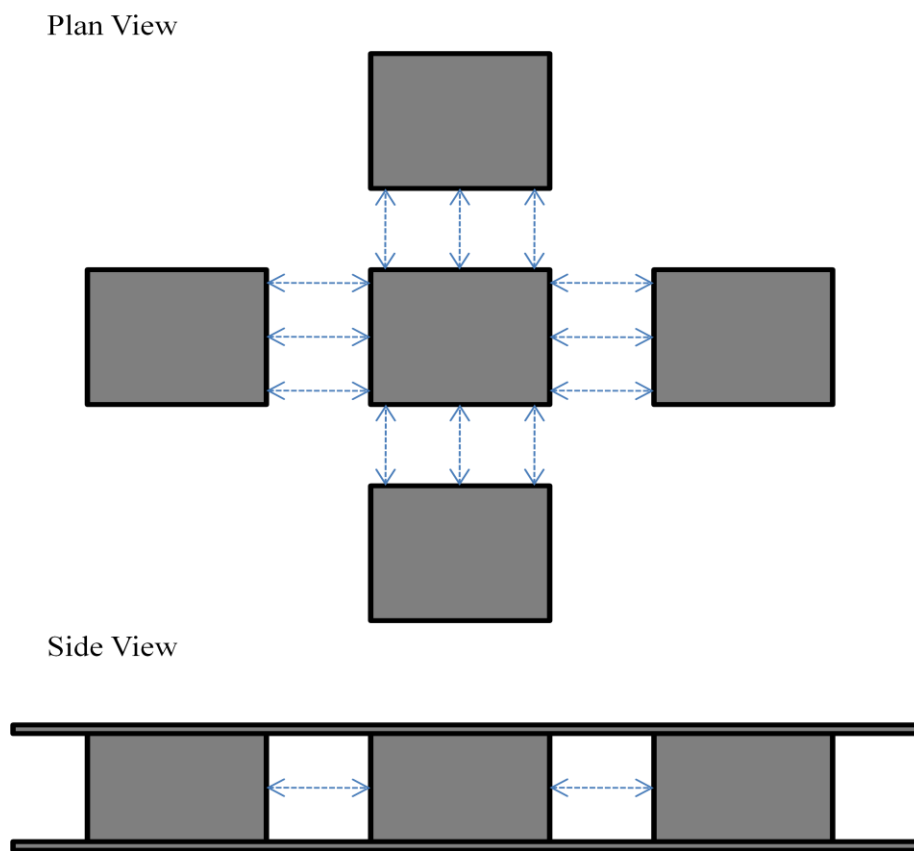


Figure 4.3: Illustration of position of measurements

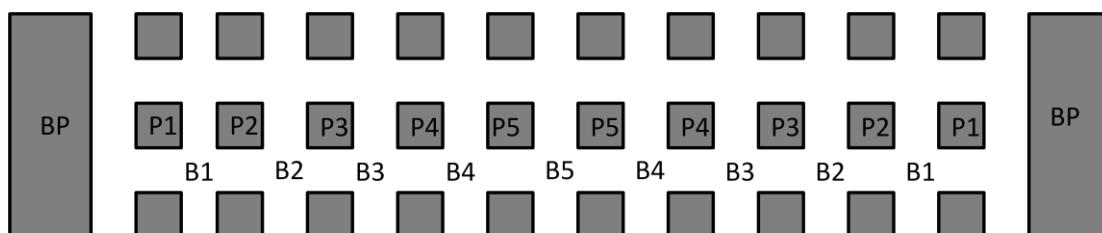


Figure 4.4: Pillar and Bord nomenclature in relation to panel layout, used in measurements and analysis.

The absence of the original centre line due to pegs falling out because of scaling of the roof made it difficult to offset the pillars and determine the exact location. However pillar areas could still be calculated from basic geometry.

4.5 Results and Analysis

The results from the measurements of the bords across Morupule's West Main Development Panel are summarised graphically in figure 4.5. The graph indicates that the average bord widths deviate by between 1m (for bords closer to barrier pillars) and 1.6m (for bords at the middle of the panel) from the original bord dimensions.

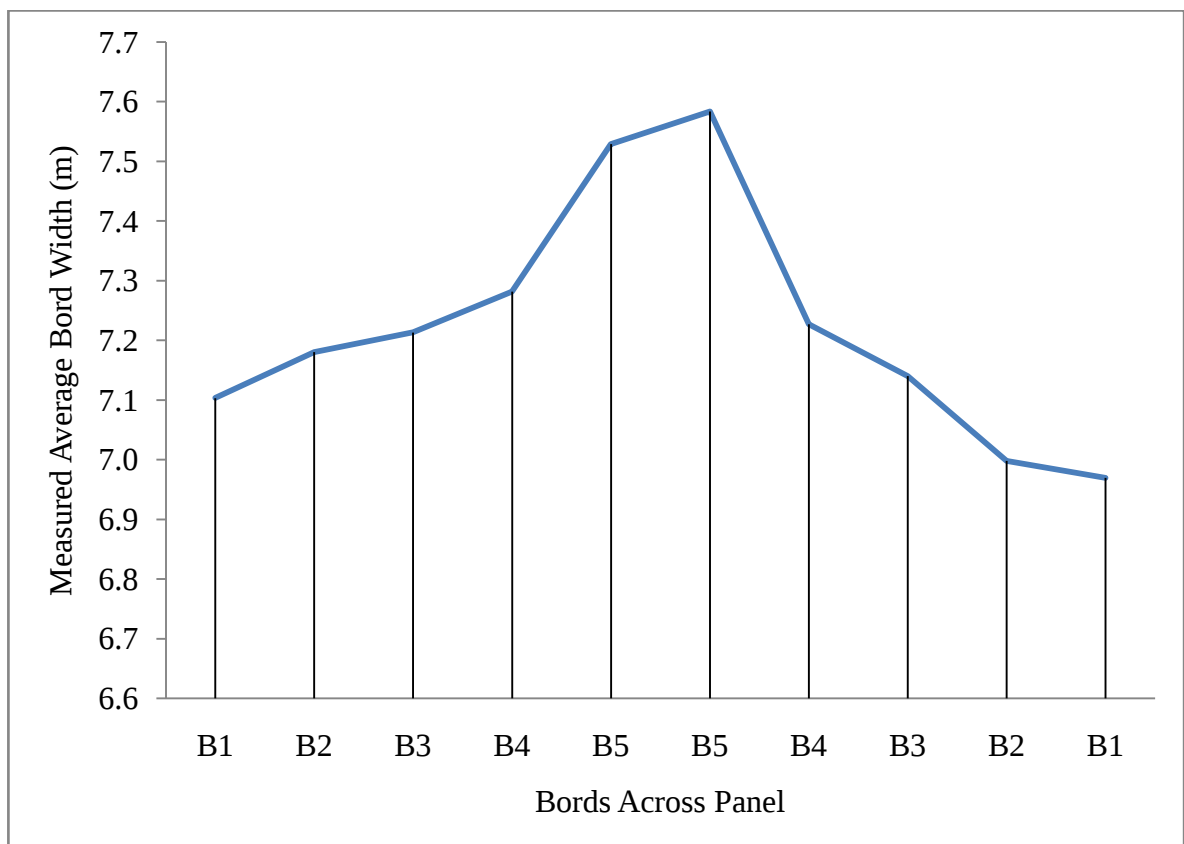


Figure 4.5: Measured average bord widths across Morupule's West Main Panel

The belt drive and the roadway are the main entrances into the Morupule underground workings and are subject to frequent examination for any unsafe conditions including scaled out material on the roof and sidewall of pillars. Such material requires barring down which effectively reduces the pillar areas and increases the mining heights. This may explain why the scaling rates are so high for centre pillars.

From the bord widths (B), where the original pillar centre distances (C) for the panel are known (18.0m), the resultant pillar widths (W) can be determined from the equation: $C = B + W$. Consequently, the effective pillar area can also be obtained.

The variation of the resultant pillar widths and area with different pillars across the panel is shown in figures 4.6 and 4.7.

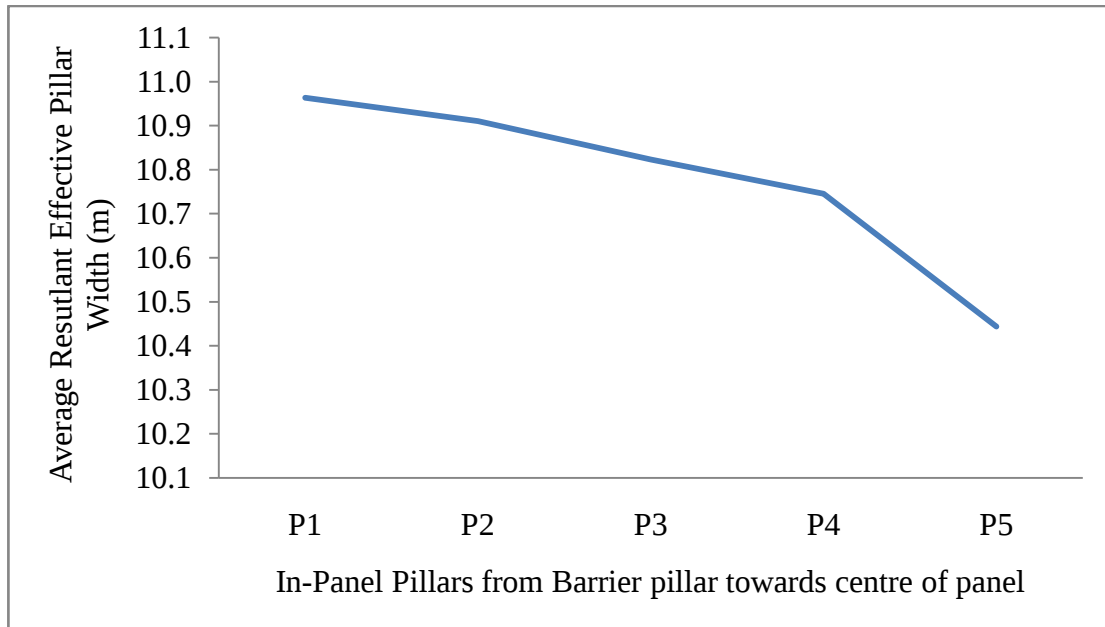


Figure 4.6: Average effective widths for In-Panel pillars from barrier pillar towards centre of panel

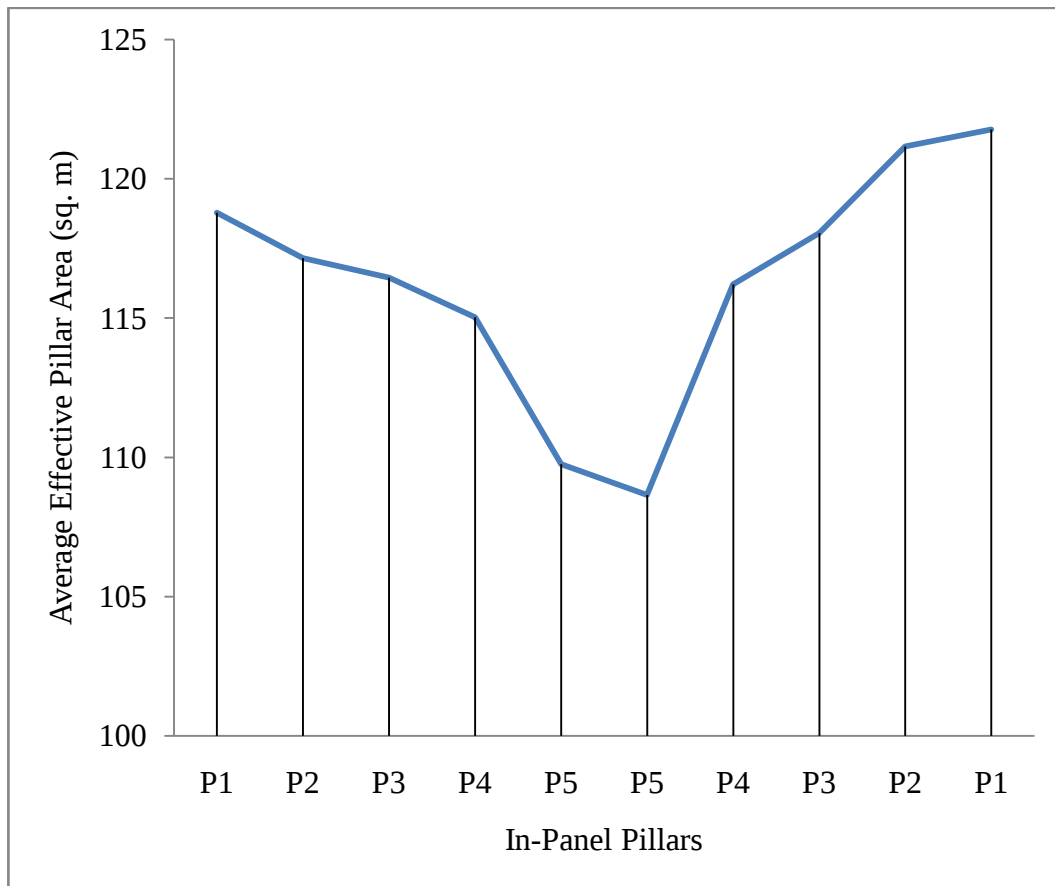


Figure 4.7: Distribution of Average Effective Pillar Area across the panel

A reduction in the area of a pillar means increased stress on the pillar, according to the tributary area theory described in Chapter 1 (equation 2.1).

Figure 4.8 illustrates the average increase in pillar loading towards the centre of the panel.

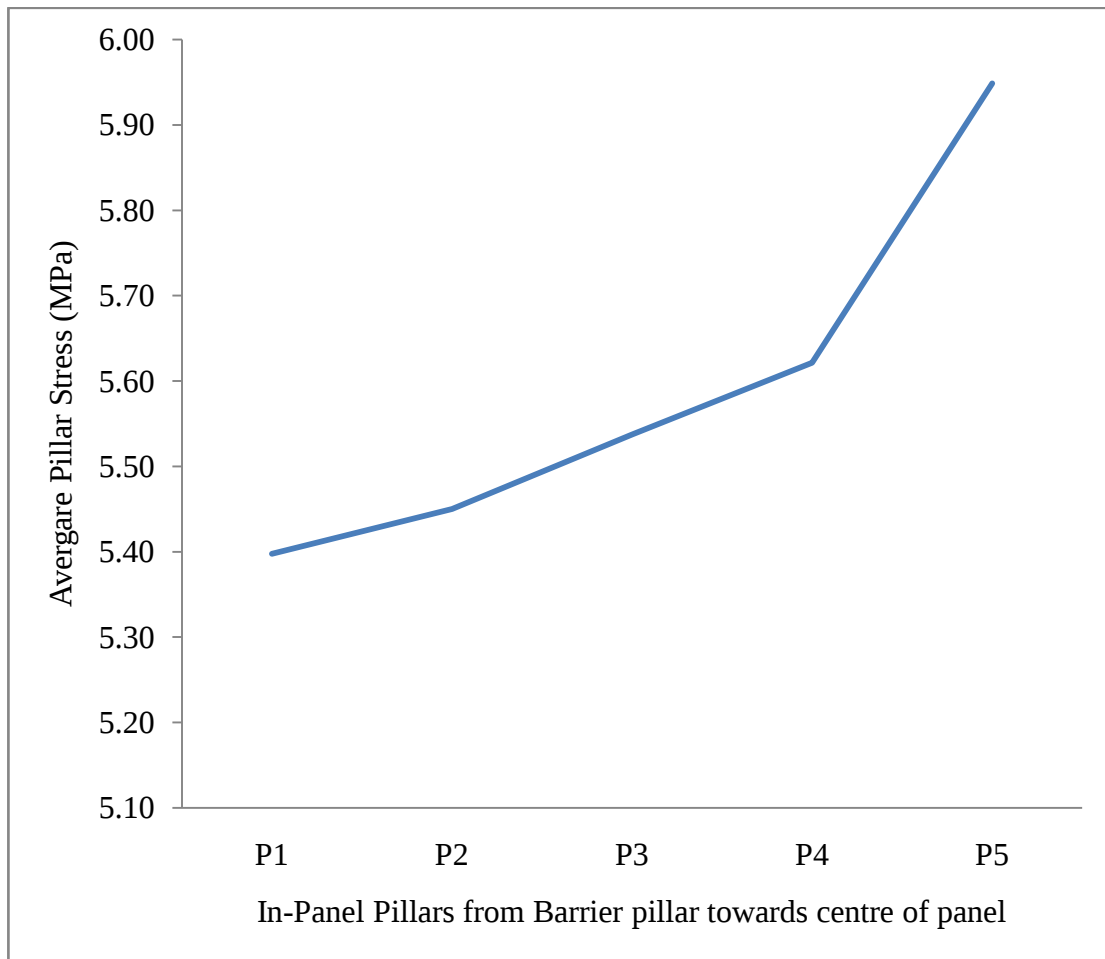


Figure 4.8: Increase in pillar loading towards centre of panel

As mentioned earlier and represented in figure 4.9, a reduction in pillar size results in a decrease in pillar strength, as the width to height ratio of a pillar is directly proportional to its strength.

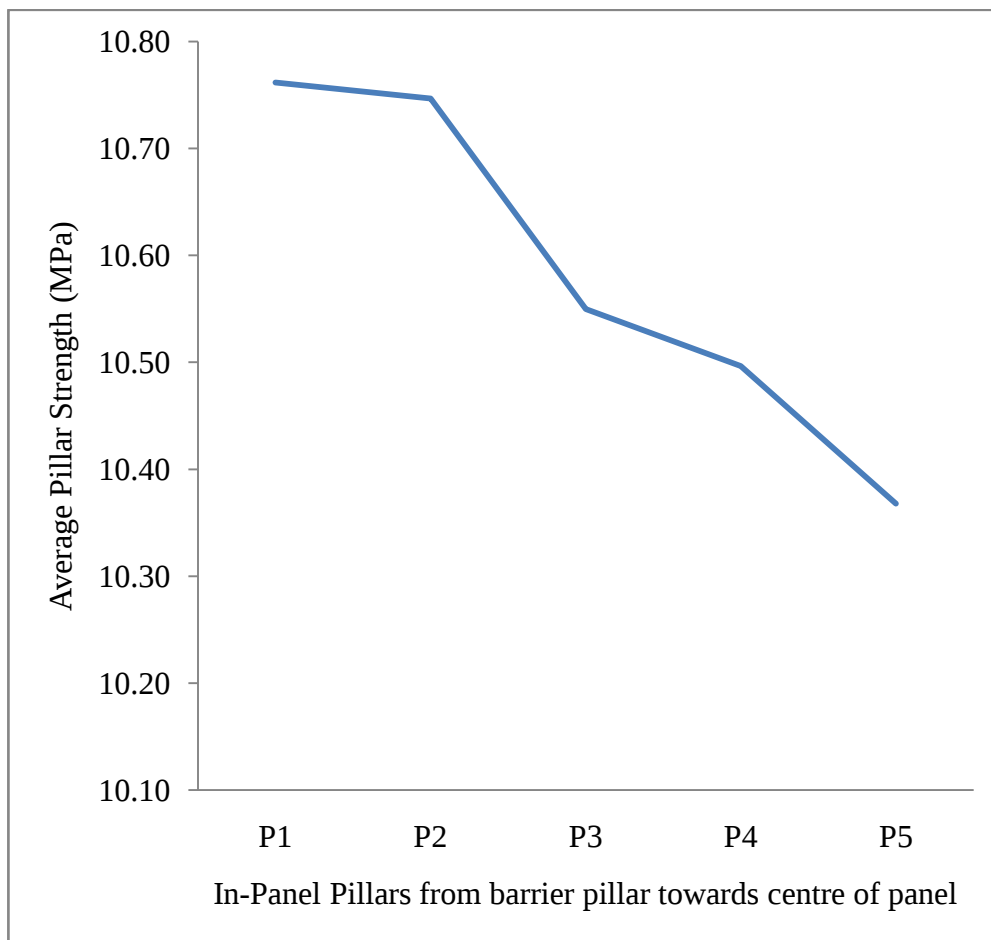


Figure 4.9: Decrease in In-Panel Pillar strength.

Because safety factor is the ratio of pillar strength to pillar stress, it follows that safety factor decreases from P1 pillars towards the centre of the panel (Figure 4.10). The design safety factor for Morupule's West Main Panel is 2.4 and from this analysis safety factors have dropped to between 2.0 and 1.75 over a period of more than 30 years.

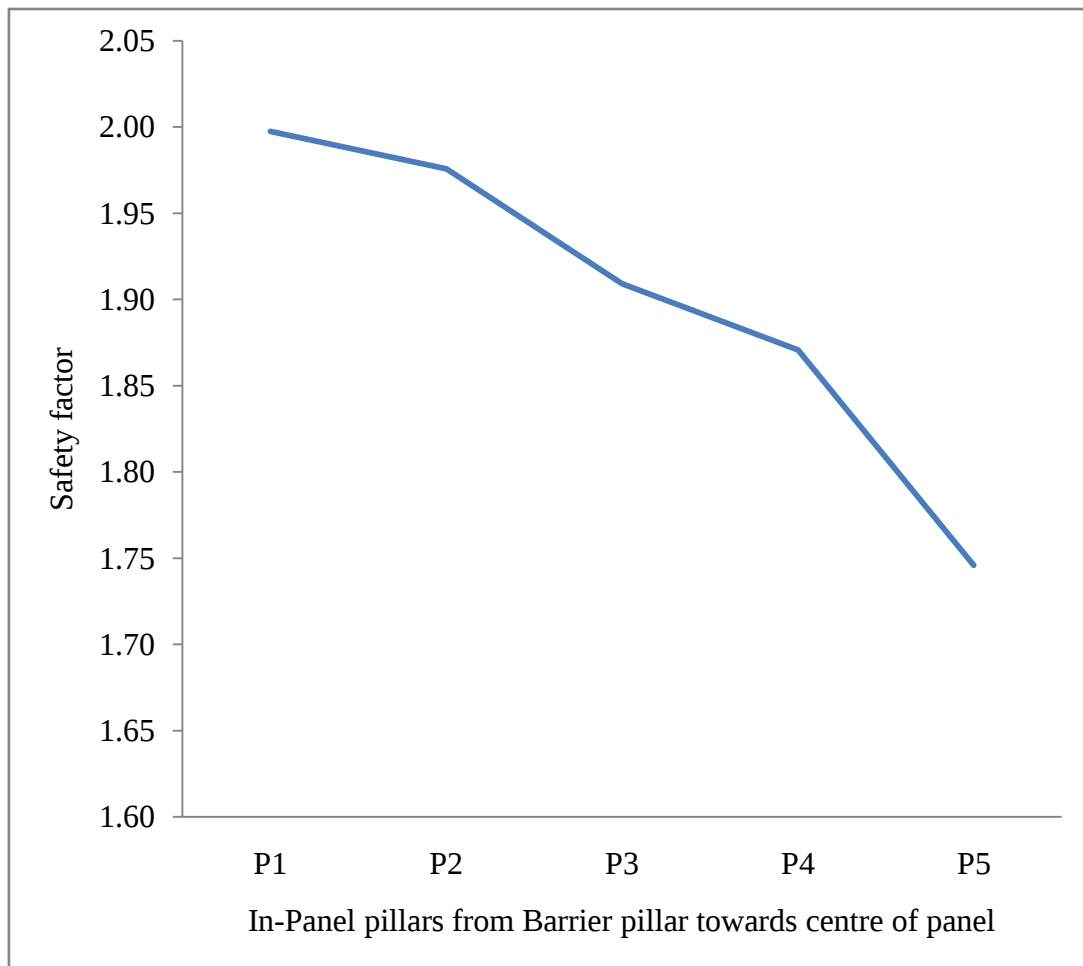


Figure 4.10: Pillar safety factors

4.6 Conclusion

It should be noted that pillar scaling is affected by a number of factors that include: amount of weathering, inherent faults and fractures in the pillar, as well as pillar strengths (Van der Merwe, 2005 and Esterhuizen, 1997). The exercise has assumed that the effects due to these remain the same across the panel. The outcome of investigation is that centre pillars in a panel are generally subjected to higher scaling rates than those next to barrier pillars, possibly by increased loads at the centre of the panel. It thus maybe suggested that pillars next to barrier pillars have part of their load transferred to the barrier pillars, as also revealed in the numerical modelling described in Chapter 3.

The practical exercise has been limited to the determination of the impact of pillar scaling on the pillars in a bord and pillar layout. The time dependent stability factors have not been determined, but it is reasonable to assume that due to the lower stresses experienced by P1 pillars, these pillars will have a slightly longer life than the pillars in the middle of the panel. When remedial action is to be taken in curbing pillar scaling through pillar strapping, shotcrete or sand filling, more attention should be given to pillars in the middle of the panel. It should be noted that cleaning of scaled material reduces confinement in the affected pillars and may lead to further scaling.

CHAPTER 5

Design and Analysis of Potential Alternative Bord and Pillar Geometries

5.1 Introduction

In Chapter 3, numerical modelling of bord and pillar layouts using the LaModel software package has shown that pillars all in a panel are not subjected to the same vertical stresses. Thus they have different safety factors. Pillars closer to barrier pillars (P1 pillars) exhibit lower stresses than those in the middle of the panel (P2 Pillars). This has also been verified by underground investigations on pillar scaling carried out at Morupule Colliery as detailed in Chapter 4. Both outcomes may lend confidence to the possibility of increasing extraction through resizing or repositioning of pillars without affecting the overall stability of workings adversely.

This chapter investigates the effects of reducing the size of the P1 pillars, repositioning of central pillars and barrier pillar pocketing with the aim of developing alternative pillar geometries which offer improved extraction whilst maintaining stable conditions.

5.2 Design Methodology

The design of alternative pillar geometries is based on an optimization procedure that utilizes pillar strain safety factors across all the pillars in a panel. Three main modelling design options are considered, focusing on the following:

- Resizing of P1 pillars
- Repositioning and sizing of centre pillars
- Barrier pillar pocketing

In the design options, the intent is to determine precise safety factors and optimize pillar sizes for mine design. The result of each modeling sequence is used to identify on a relative basis:

- General stability of all pillars, represented by safety factor
- Proneness to failure, represented by seam convergence
- Potential to contribute to significant failures, represented by vertical stress

Identification of the weakest pillars (lower safety factor pillars) and variance of the SF range for pillars can provide comparable results for determining design adequacy.

The same models at 50, 100, 150 and 200m depths as in Chapter 3 have been used in the analysis. When the results from the four base case models are reviewed, a comparative process is used to identify areas of increased convergence, vertical stress levels and the relative strain safety factor changes.

5.3 Design option 1: P1 pillar size reduction

5.3.1 Design 1.1

This option aims at reducing the safety factors of P1 pillars through reducing their sizes and increasing the bord width between them and the barrier pillar as illustrated in figure 5.1.

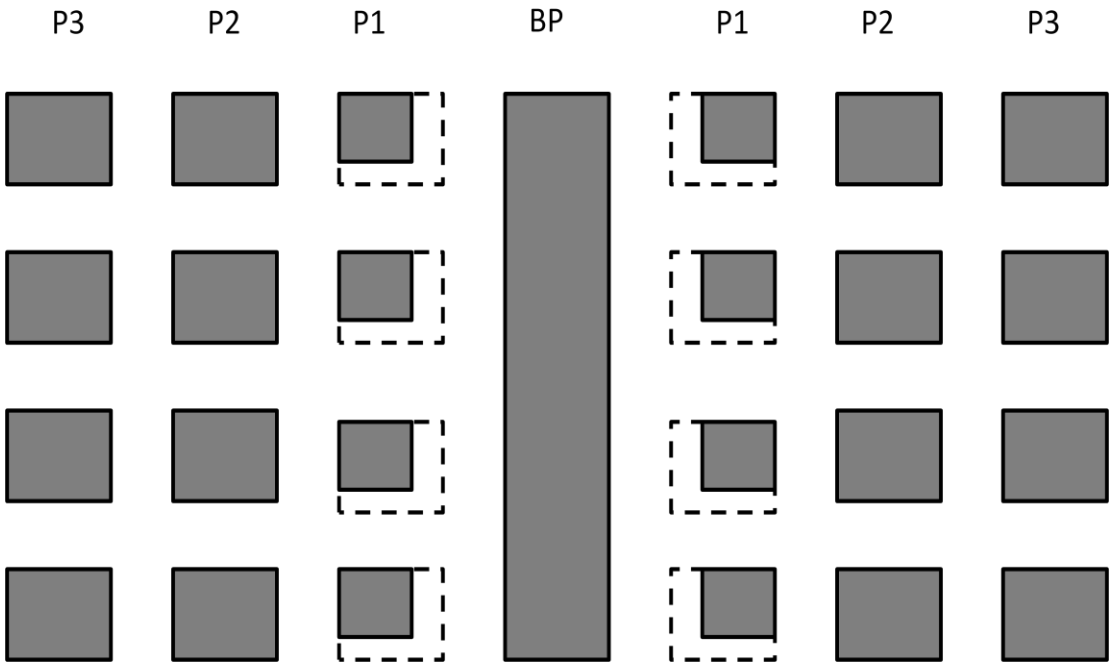


Figure 5.1: P1 pillar size reduction for design option 1.1

Reducing P1 pillar sizes also has an impact on the stability of other pillars. In order to minimize the effects of P1 pillar reduction on the other in-panel pillars, “robbing” of

the pillars takes place only on the sides closest to the barrier pillar. The P1 pillars are resized until their safety factor is similar to the safety factors of the rest of the pillars.

Figures 5.2 and 5.3 compare the safety factors of the pillars at 50m depth as P1 pillar sizes are reduced.

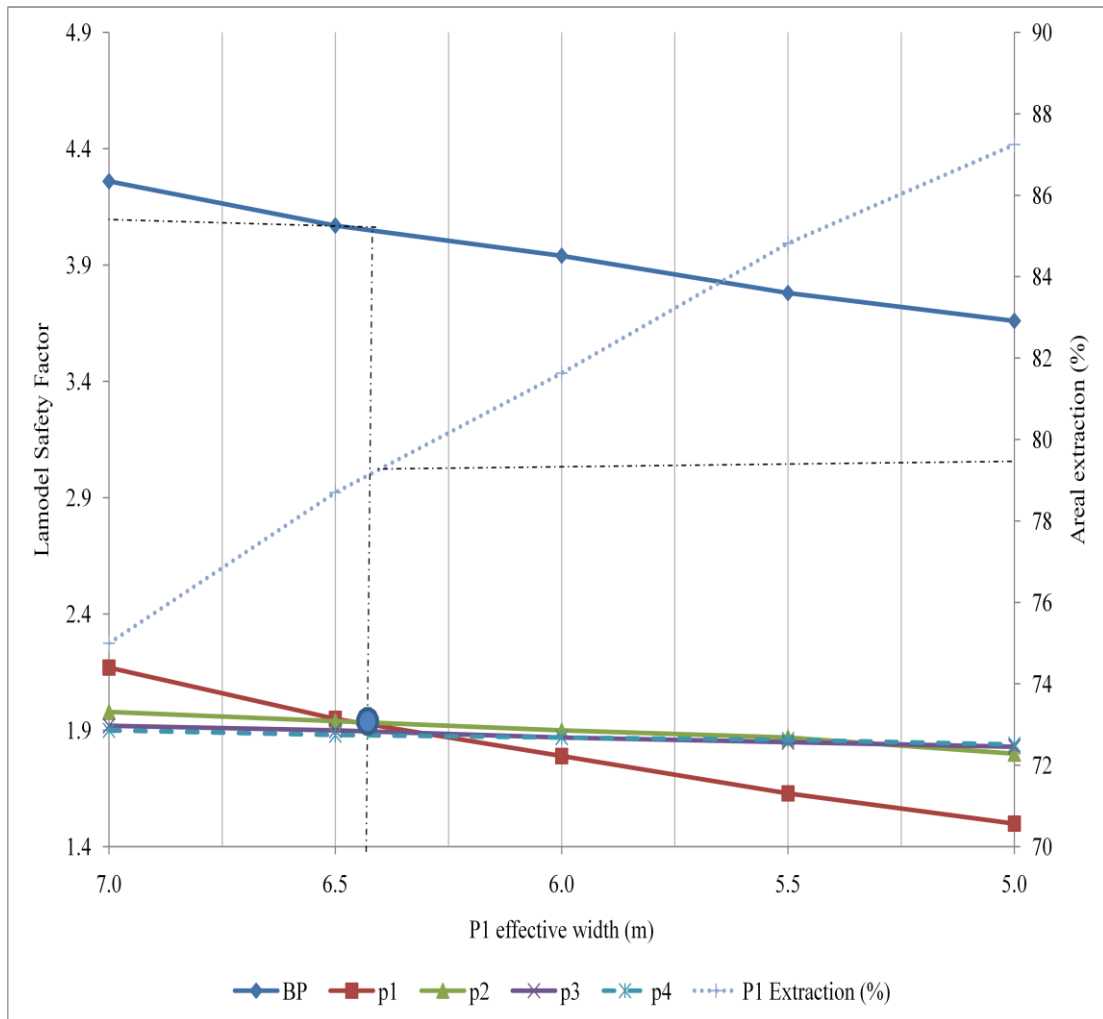


Figure 5.2: Lamodel Safety Factors for design option 1.1 at 50m depth

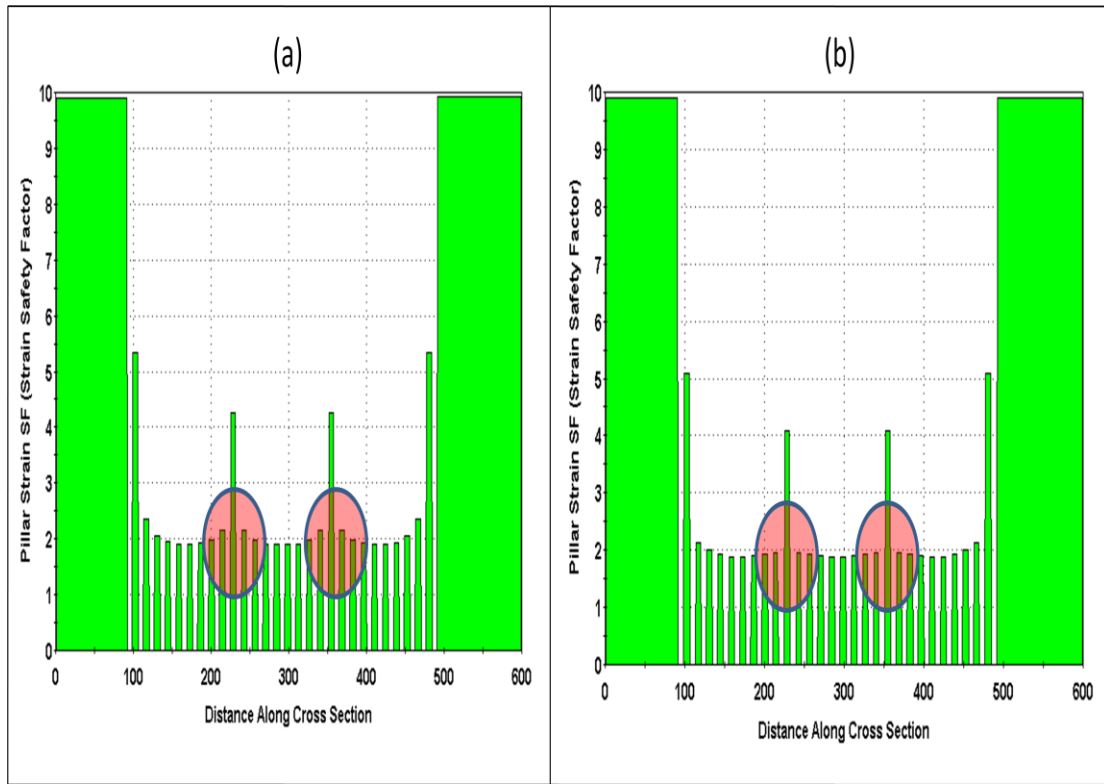
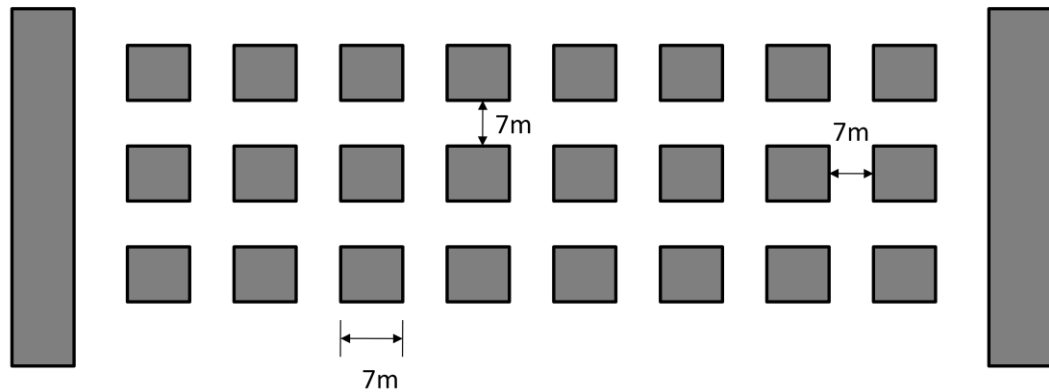


Figure 5.3: Safety factor comparison (a) original and (b) design option 1.1

In figure 5.3 it can be seen that P1 safety factor becomes equal to P2 safety factor (figure 5.3b) when its effective width is approximately 6.4, the new layout for the panel at 50m depth will be as presented in figure 5.4 below.

(a) Original design



(b) Design option 1.1

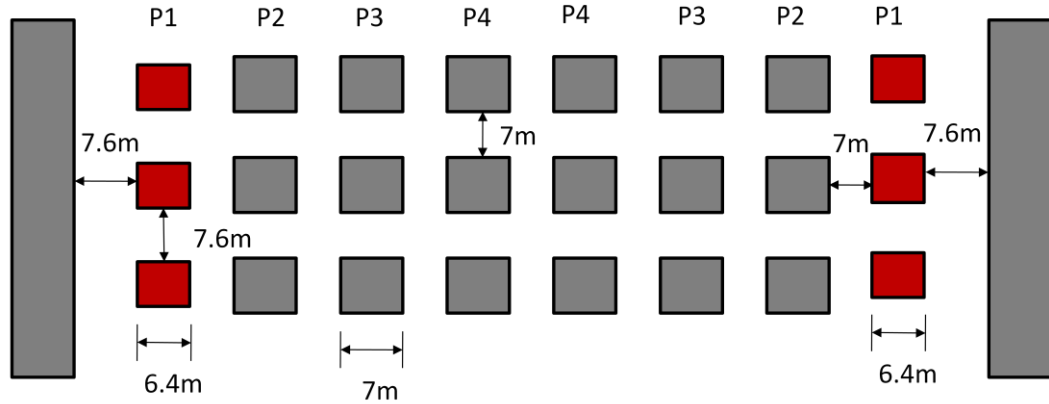


Figure 5.4: Change in pillar layout on a roadway panel at 50m depth for design option 1.1

To achieve practical application of this option, a design consisting of rectangular P1 pillars is considered. In order to achieve the same safety factor across the panel as shown in the figure below, P1 pillars will have to measure 6m x 7m, giving an effective pillar width of 6.46m.

Although the same safety factor across the pillars is achieved by this layout, modeling still shows that P1 pillars are at slightly higher total vertical stress levels than the rest of the in-panel pillars (figure 5.5). The new design indicates that the maximum

vertical stresses within the panel will be about 0.6% higher than those in the initial layout, indicating low potential for significant failure. Similarly, the changes in seam convergence are minimal.

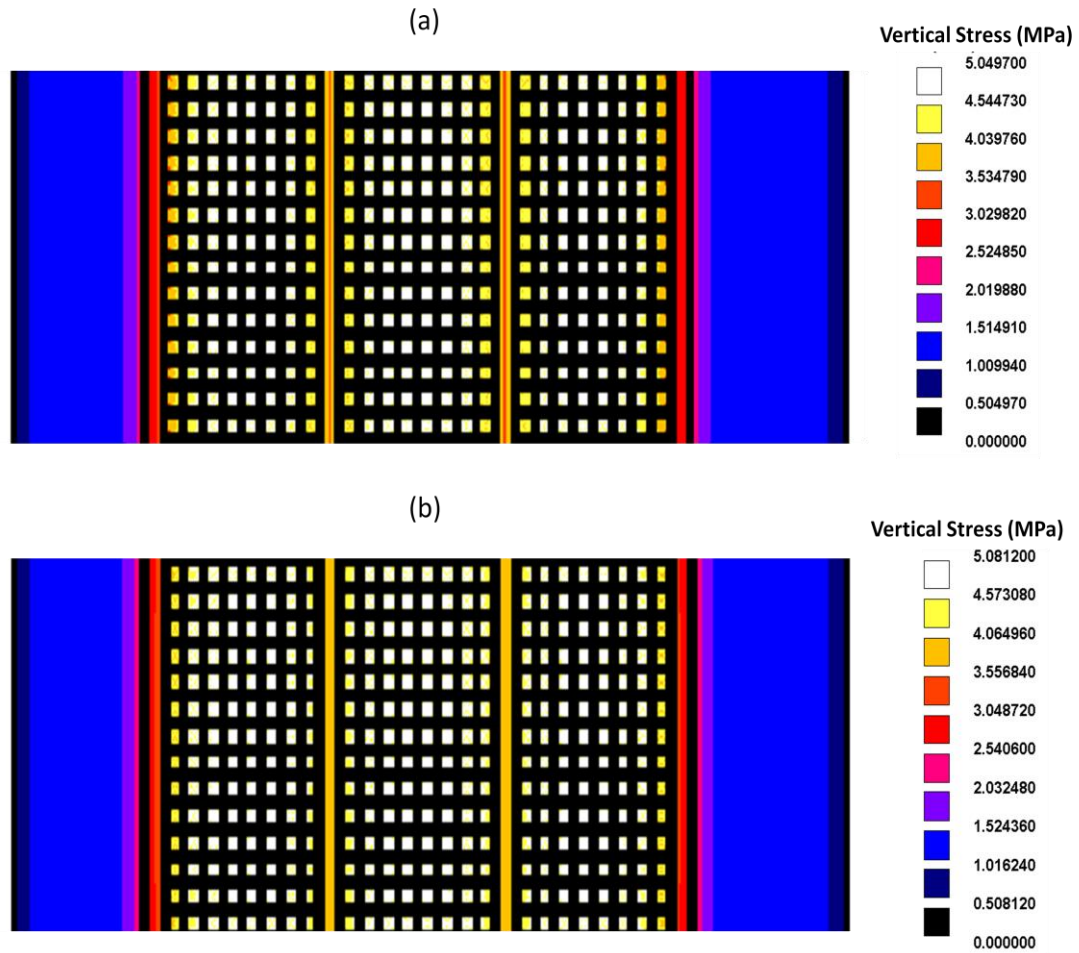


Figure 5.5: Total vertical stress for (a) initial layout and (b) design option 1.1 at 50m depth.

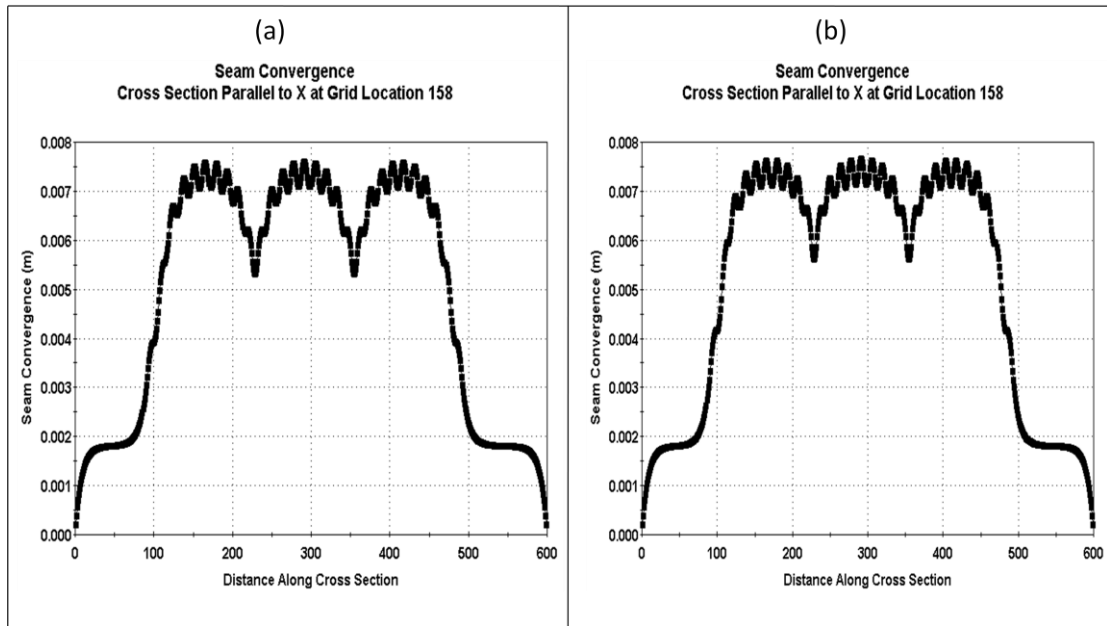


Figure 5.6: Seam convergence for (a) initial layout and (b) design option 1.1 at 50m depth

In this design, the areal extraction for the mining of P2 pillars remains as given by the extraction formula in Chapter 2 (equation 2.6). For the mining of P1 pillars, the same formula can be modified to give:

$$e_2 = 1 - (A_x / C^2) \dots\dots\dots \text{Equation 5.1}$$

Where A_x is the new P1 pillar area.

Consequently, overall areal extraction taking barrier pillars into account will be given by:

$$e_o = 1 - \left\langle \left\{ (n-2)w^2 + A_x + CL \right\} / \left\{ C[l + (n-1)C + B] \right\} \right\rangle \dots\dots\dots \text{Equation 5.2}$$

Equation 5.2 has been modified from equation 2.7 in Chapter 2.

From the above equations, P1 pillars will be mined at an effective areal extraction rate of 79.1%, an increase of 4.1% from 75% at 50m depth. Consequently, panel overall extraction increases by 3.3% from 69.4% to 72.7%.

Increasing the bord width requires an investigation into the bolt density for roof support. Assuming that the roof material to be supported is made up mainly of shale of density 1800kg/m^3 and a roof support safety factor of 1.5 is required for a beam of thickness $t = 0.6\text{m}$,

The number of bolts n required per m^2 for the original layout will be:

$$n = SF * \rho * g * t / (Pf) \dots\dots\dots \text{Equation 5.3}$$

$$n = 0.055\text{bolts} / \text{m}^2, \text{ each bolt supports } 18\text{m}^2$$

Where:

- SF = safety factor (minimum 1.5)
- ρ = density of suspended strata (kg / m^3)
- g = gravitational acceleration ($9.81 \text{ m} / \text{sec}^2$)
- Pf = yield load of bolt (kN)
- t = beam thickness (m)

Bolt spacing required is 1 bolt every 4.24m (4.24m grid)

In the original design, the number of bolts required in a single row will be $(7\text{m} / 4.24\text{m})$ 1.7 and for the proposed design will be $(7.6\text{m} / 4.24\text{m})$ 1.8. This means the support layout for both cases will have two bolts per row. Thus there will not be an increase in the number of bolts when the new method is applied.

However, an increase in bord width will result in an increase in the amount of sag, as described in Chapter 2. The change in the amount of sag as a result of the application of new design, $\Delta\eta$, will be given by:

$$\Delta\eta = \{(L^4 - L_o^4)/L_o^4\} * 100\% \dots\dots\dots \text{Equation 5.3}$$

L and L_o are the new and original bord widths between the barrier pillars and P1 pillars respectively. For this model, there will be an increase of about 39% in the amount of sag. This means the time elapse between exposing the roof and installing bolts in the new design will have to be minimized and also the bolting equipment should be able to apply the right amount of pre-tension to the roof. Figure 5.7 shows the variation of Lamodel safety factors for improved design at 100m depth.

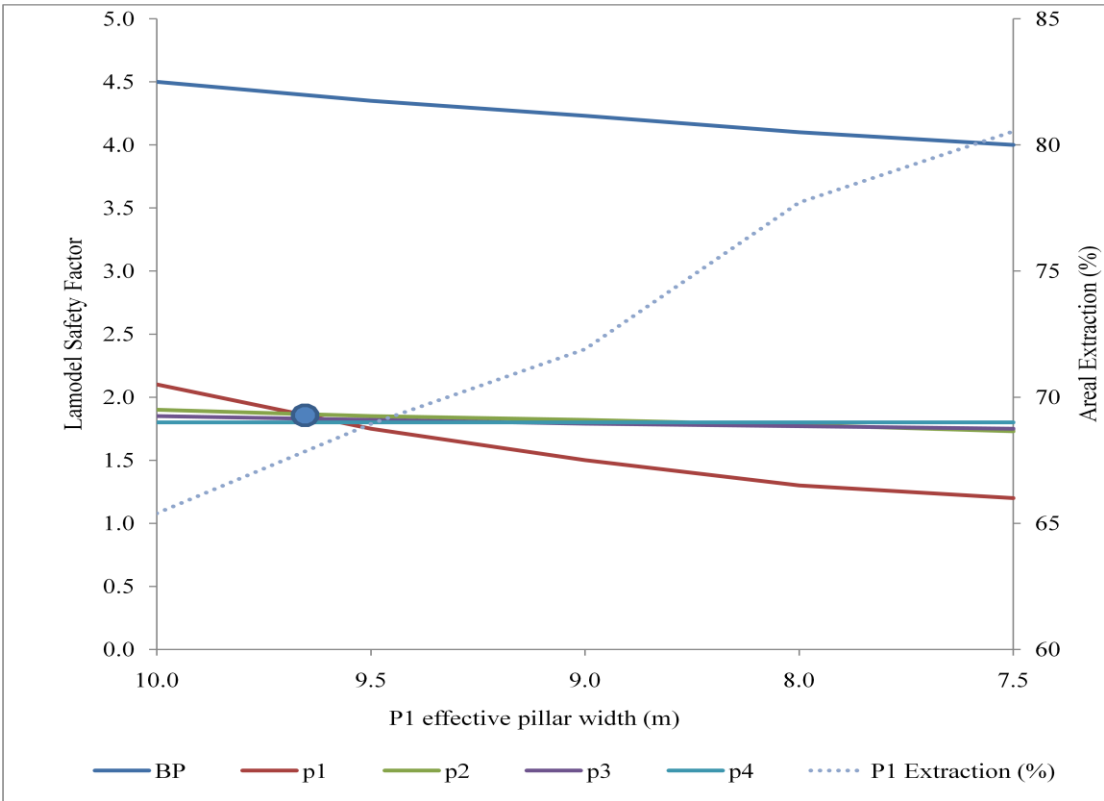


Figure 5.7: Lamodel safety factors for design option 1.1 at 100m depth

The effective width of P1 pillars at 100m depth will be approximately 9.6 and the alternative design will be as shown in figure 5.8. The variation of safety factor with decrease in P1 pillar width at 150m and 200m depths is shown in figure 5.9.

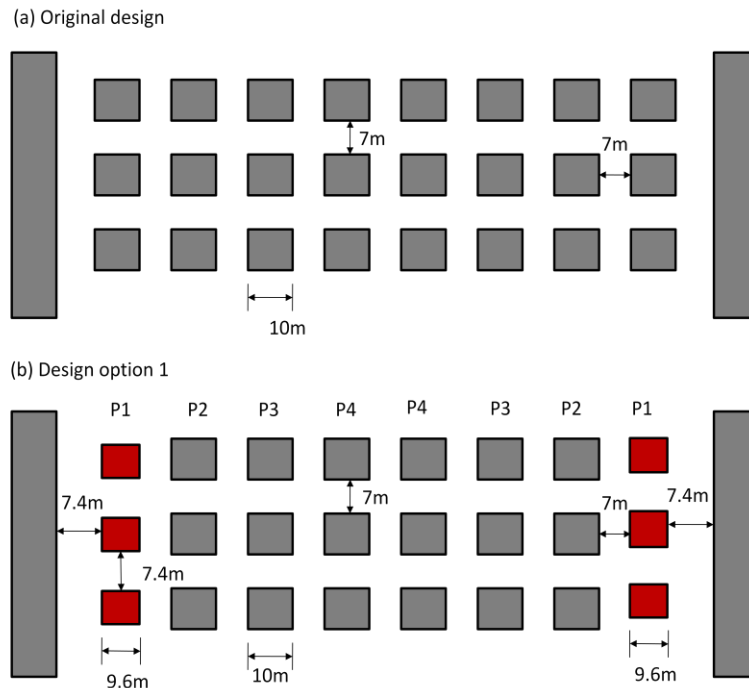


Figure 5.8: Change in P1 pillar dimensions for improved design at 100m depth

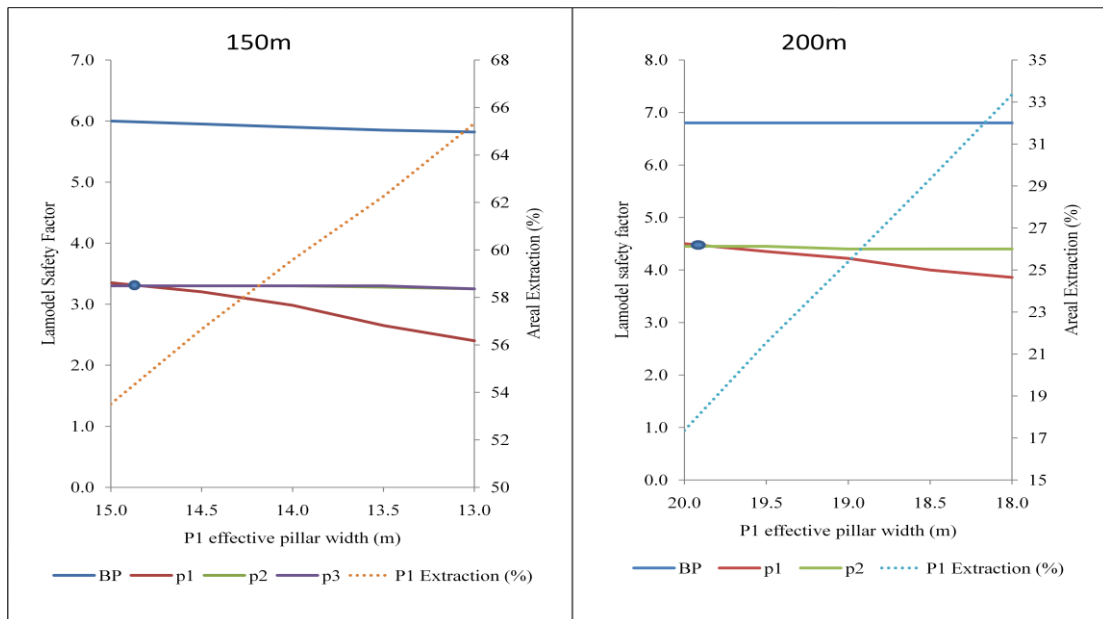


Figure 5.9: Safety factor variations with decrease in P1 pillar width at 150 and 200m depths.

Table 5.1: Summary of design option 1.1 parameters

Depth	50m	100m	150m	200m
In-panel pillar width (m)	7	10	15	20
P1 effective pillar width (m)	6.4	9.6	14.8	19.9
Bord width between in-panel pillars (m)	7	7	7	7
Bord width between P1 and BP pillars (m)	7.6	7.4	7.2	7.1
Areal extraction (%) - original	75.0	65.4	53.5	45.1
P1 areal extraction (%)	79.1	68.1	54.7	45.7
Increase in P1 areal extraction (%)	4.1	2.7	1.2	0.6
Overall areal extraction (%) - original	72.2	62.7	50.4	41.3
Overall areal extraction (%) – new design	72.7	63.0	50.6	41.40
Increase in panel overall extraction (%)	0.5	0.3	0.2	0.1

Table 5.1 gives a summary of design option 1.1 parameters and a comparison of extraction (also illustrated in figure 5.10). For the same bord width at different depths, the effective width for the P1 pillars that maintains stable bord and pillar workings becomes less when compared with the rest of the pillars in the panel. Consequently, bord widths between the barrier pillars and the P1 pillars are also reduced, resulting in a reduction in extraction and amount of roof sag.

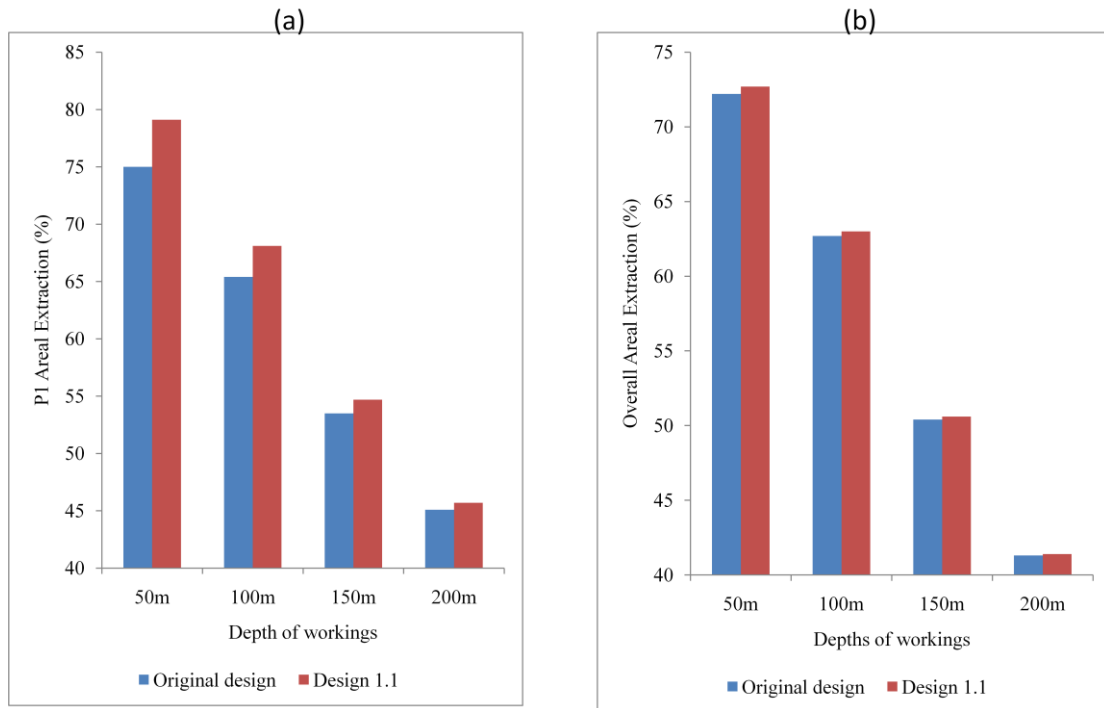


Figure 5.10: Extraction comparison (a) P1 areal extraction and (b) Overall panel extraction.

5.3.2 Design option 1.2

The second component of design option 1 involves reducing the size of P1 pillars by slicing them at the corners facing the barrier pillar as shown in figure 5.11 below. The P1 pillars are reduced in size by splitting in the direction of the barrier pillars.

Extraction ratios for Option 1.2 are determined by the same equations as those for Option 1.1.

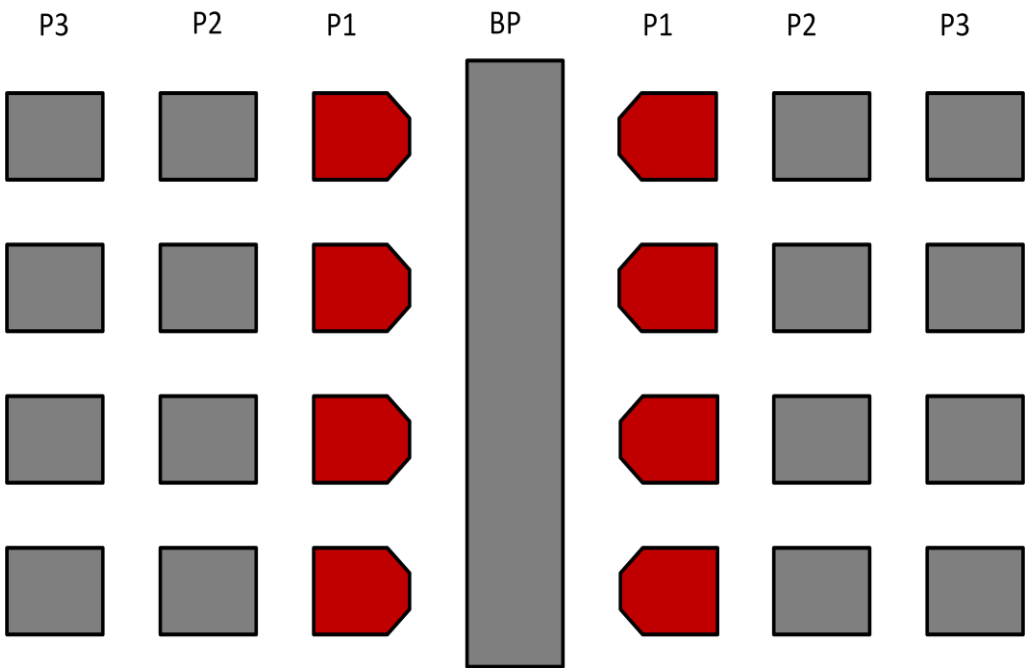


Figure 5.11 Illustration of design option 1.2

Optimization of the above layout for different depths gives the final pillar geometry shown in figure 5.12.

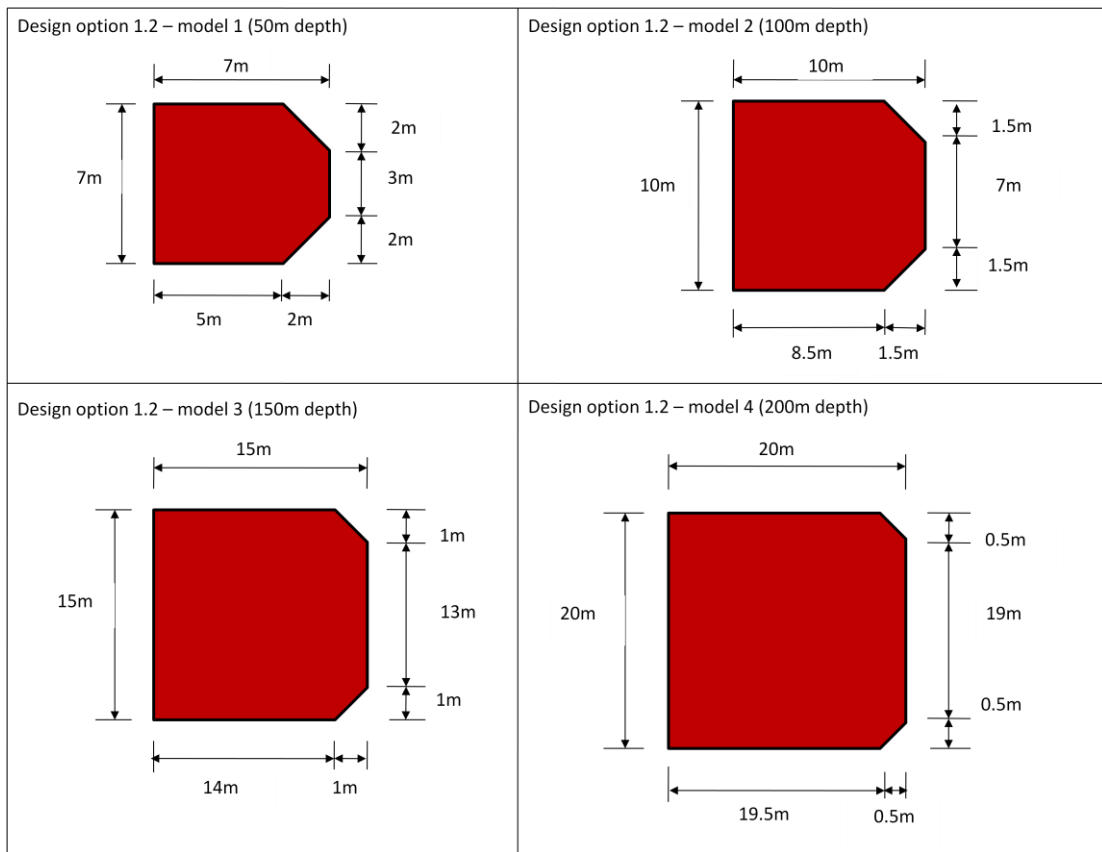


Figure 5.12: Design option 1.2 optimized P1 pillar geometries at different depths.

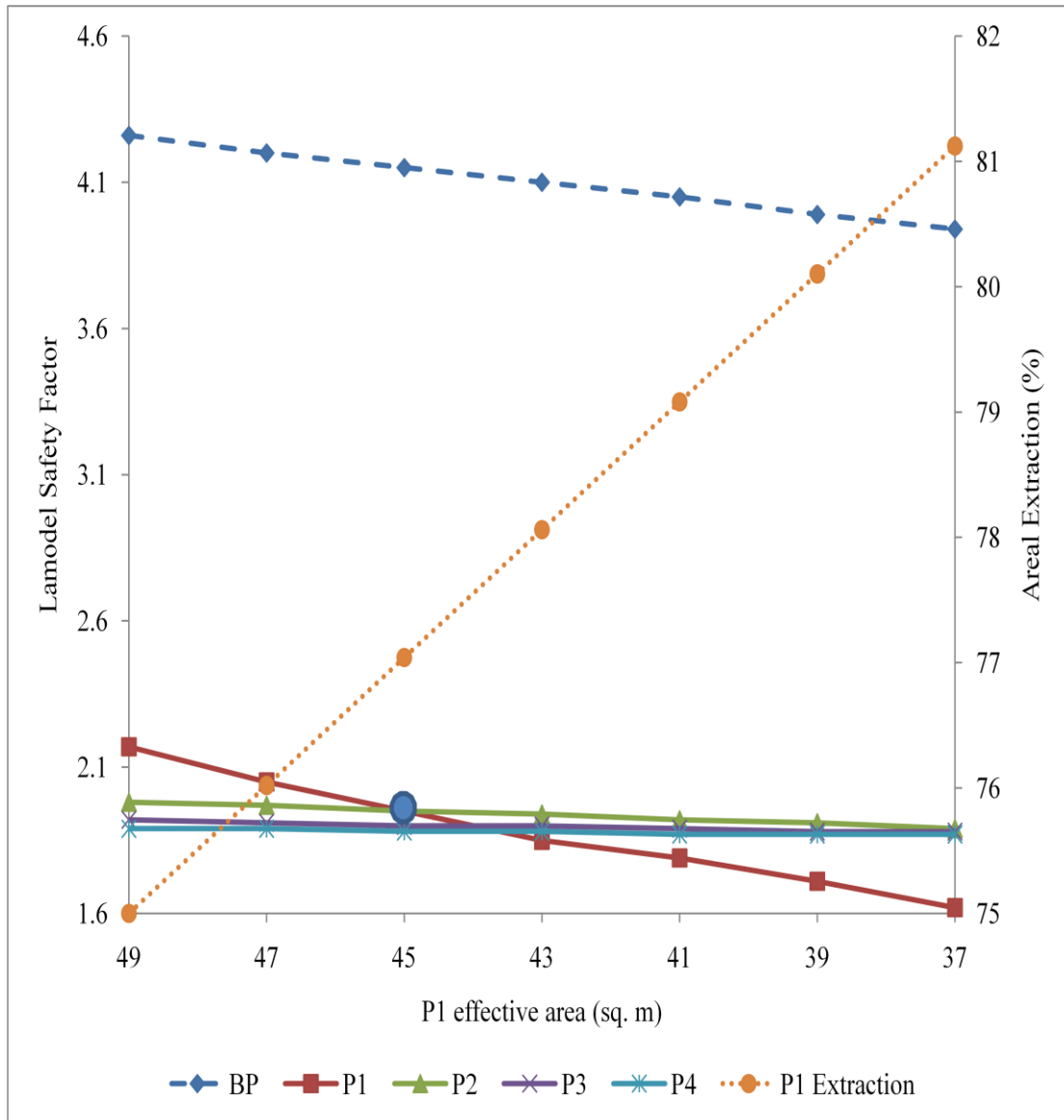


Figure 5.13: Safety factor variations with a decrease in P1 effective area at 50m depth

The figure above shows that P1 safety factor becomes equal to P2 safety factor when its area is reduced from 49m^2 to about 45m^2 . The gain in P1 areal extraction is 2% while the panel's overall extraction increases by 0.2% (given by equations 5.1 and 5.2 respectively).

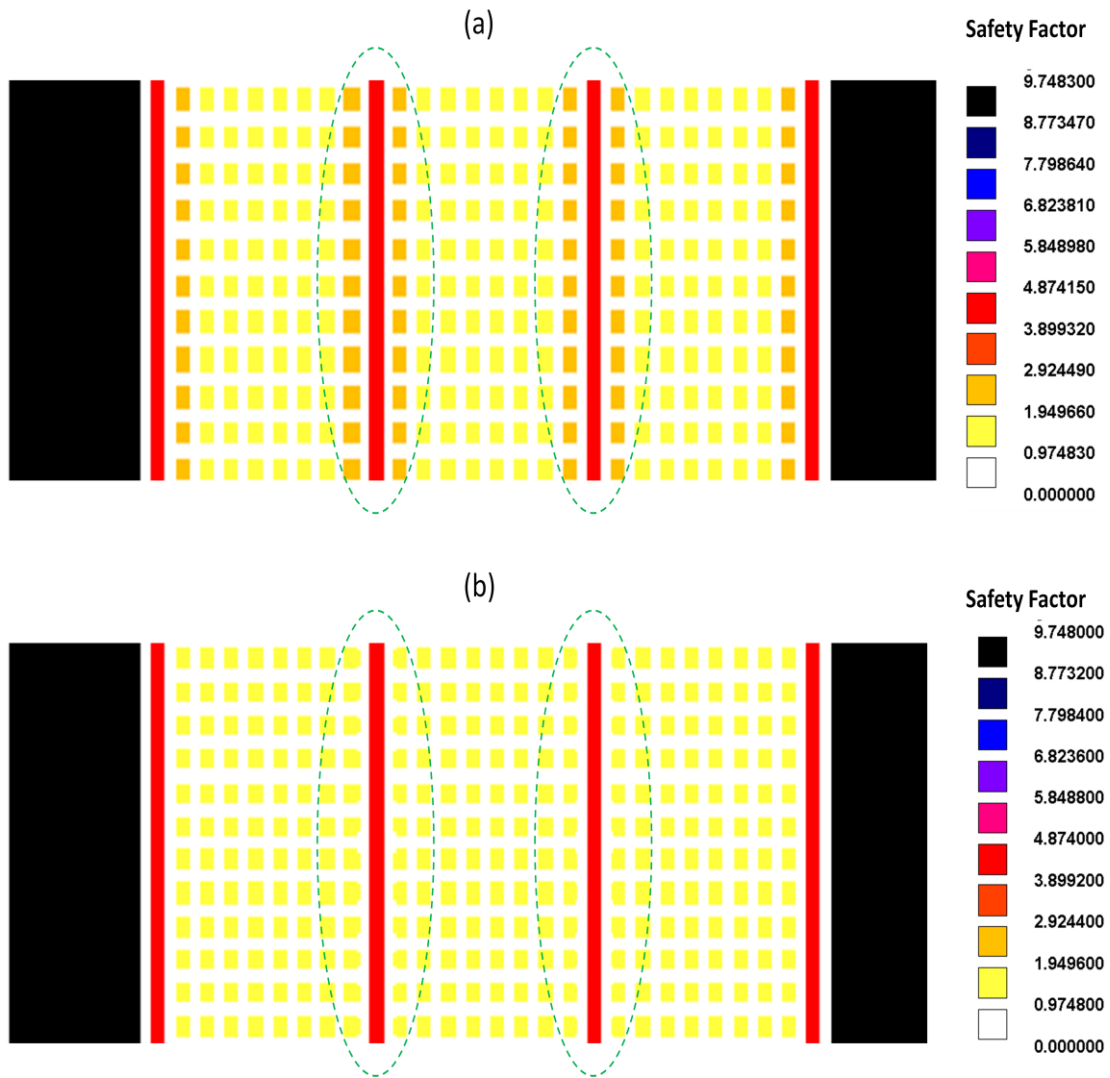


Figure 5.14: Safety factor square plot presentations

Figure 5.14 shows safety factor square plots for (a) original design and (b) design option 1.2 at 100m depths. Note P1 pillars in (b) have almost similar safety factors as the rest of the in-panel pillars.

Table 5.2: Summary of design option 1.2 parameters

Depth	50m	100m	150m	200m
In-panel pillar area (m ²)	49	100	225	400
P1 effective pillar area (m ²)	45	97.75	224	399.75
Bord width between in-panel pillars (m)	7	7	7	7
Bord width between P1 and BP pillars (m)	7.6	7.4	7.2	7.1
Areal extraction (%) - original	75.0	65.4	53.5	45.1
P1 areal extraction (%)	77.0	66.2	53.7	45.2
Increase in P1 areal extraction (%)	2.0	0.8	0.2	0.1
Overall areal extraction (%) - original	72.2	62.7	50.4	41.3
Overall areal extraction (%) – new design	72.4	62.8	50.4	41.3
Increase in panel overall extraction (%)	0.2	0.1	0.0	0.0

The application of this method means an increased room span at the intersections next to barrier pillars. This will require extra bolting for roof support in addition to support requirements specified for design 1.1.

This option also requires that the continuous miner operator has extra skills and exercises caution in slicing off the pillars closer to barrier pillars as over cutting may affect the stability of the panel. Extra time taken in setting and positioning the machine may result in reduced productivity during the mining of P1 pillars.

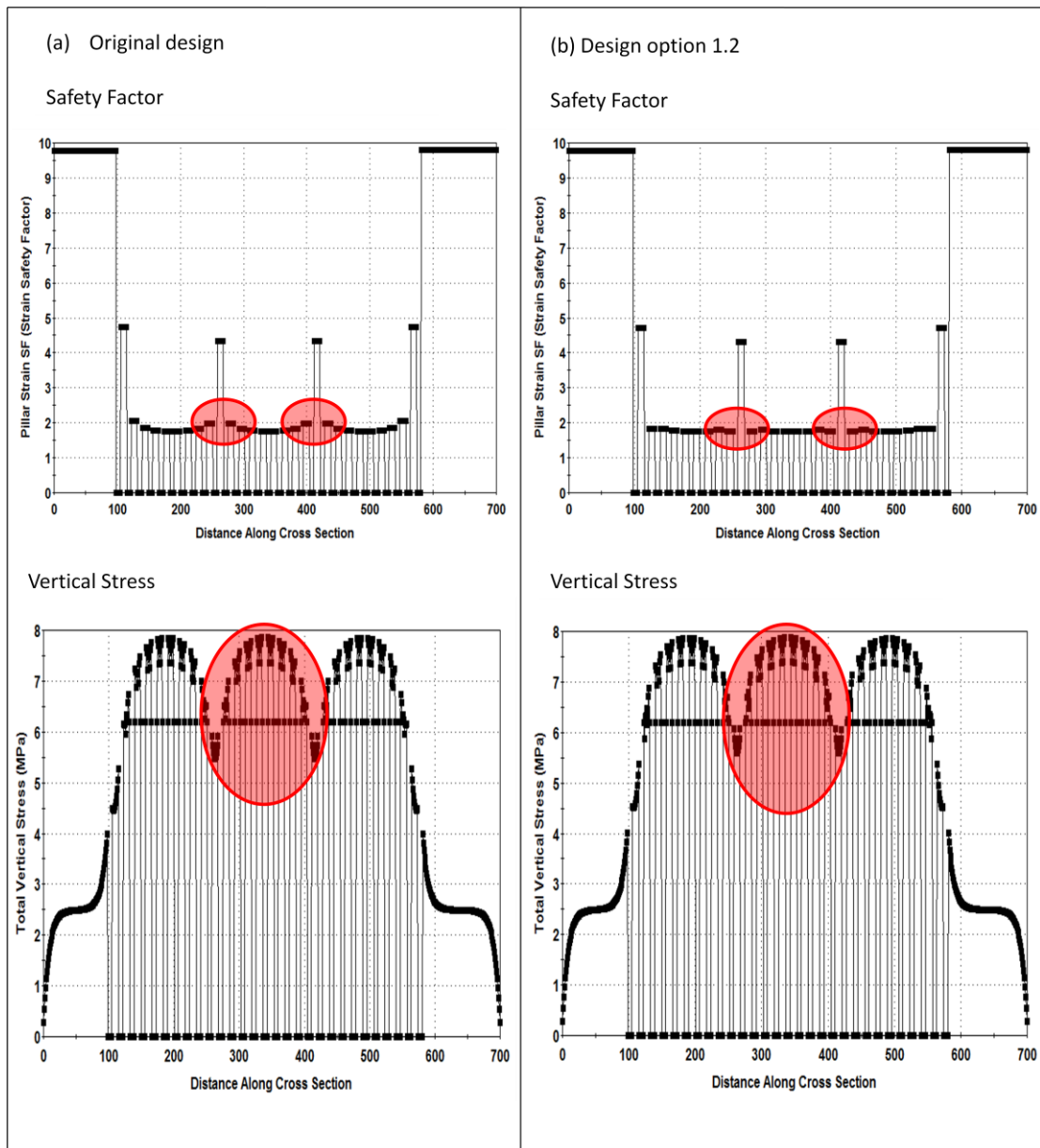


Figure 5.15: Safety factor and total vertical stress comparison for original design and design option 1.2 at 100m depth

The above figure indicates that there is very little difference in safety factor and vertical stress between design option 1.2 and the original design.

In general, design option 1.2 is more stable than design 1.1 but provides less than half the extraction increase provided by option 1.1 (figure 5.16).

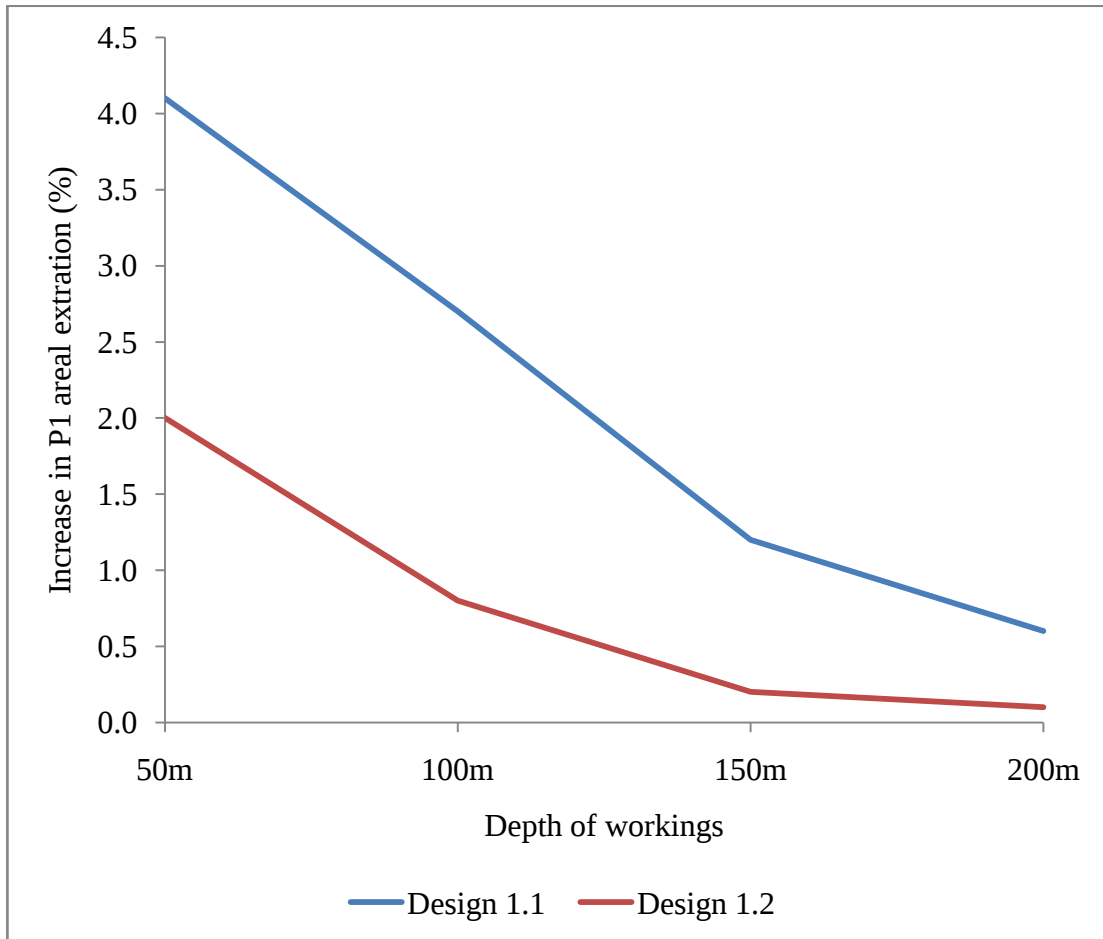


Figure 5.16 Increase in P1 areal extraction for design options 1.1 and 1.2 from original design.

5.4 Design option 2: Repositioning and sizing of panel centre pillars

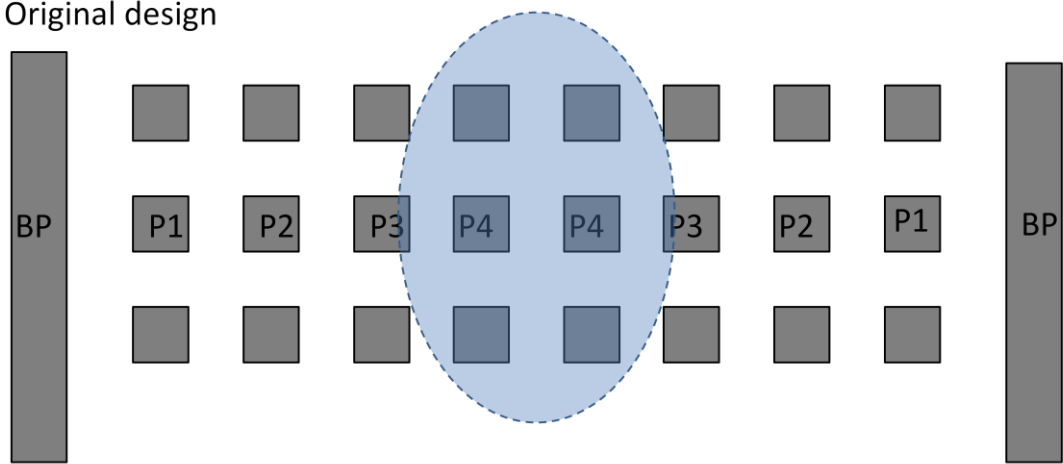
This option focuses on the centre in-panel pillars, which are at a lower safety factor (or have higher stresses) than pillars closer to the barrier pillars. The aim is to increase the safety factor of these pillars through resizing and repositioning them in two proposed ways (options 2.1 and 2.2).

5.4.1 Design option 2.1

Consider the nine roadway panel at 50m depth. The two P4 pillars at the centre of the panel can be combined by closing the roadway between them (figures 5.17 and 5.18). Effectively the panel will become an eight roadway panel. But removing one roadway reduces the panel's overall extraction by 0.3% from 72.2%. To compensate for this loss and probably increase extraction and in view of the higher safety factor (figure 5.18b) for the new P4 panel pillar, the new P4 pillar can be reduced in size. Their safety factor will have to remain higher than the rest of the pillars, because excess decrease in P4 pillar size will also affect the other pillars.

For the panels under investigations at least 49m², 70m², 105m² and 140m² at depths of 50m, 100m, 150m and 200m respectively will have to be recovered from the new panel centre pillars in order to compensate for the loss due the removal of a single roadway. Analysis of this option has shown that for smaller pillars or pillars at shallow depths, there will be no benefit compared with the original design. This is because the removal of one roadway from the original design will require smaller pillars to compensate for the loss.

Original design



Design option 2.1

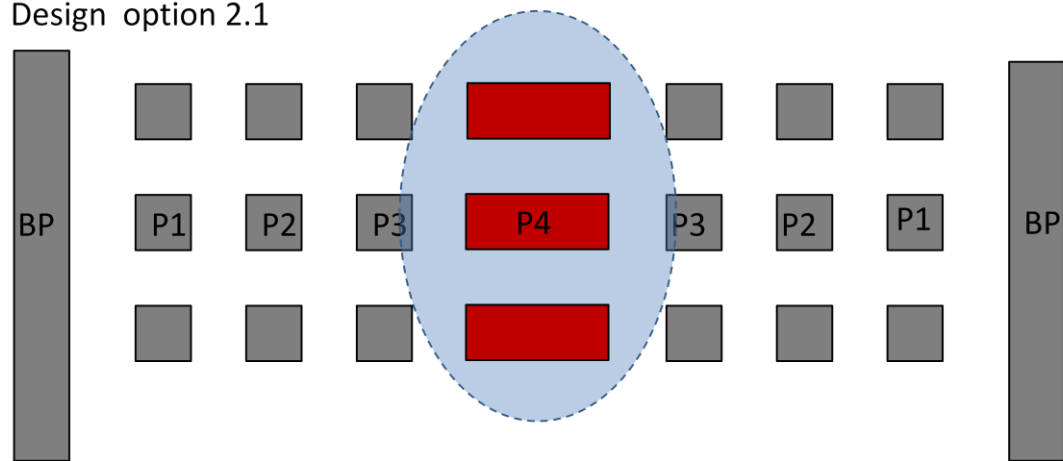


Figure 5.17 Illustration of the design option 2.1 concepts

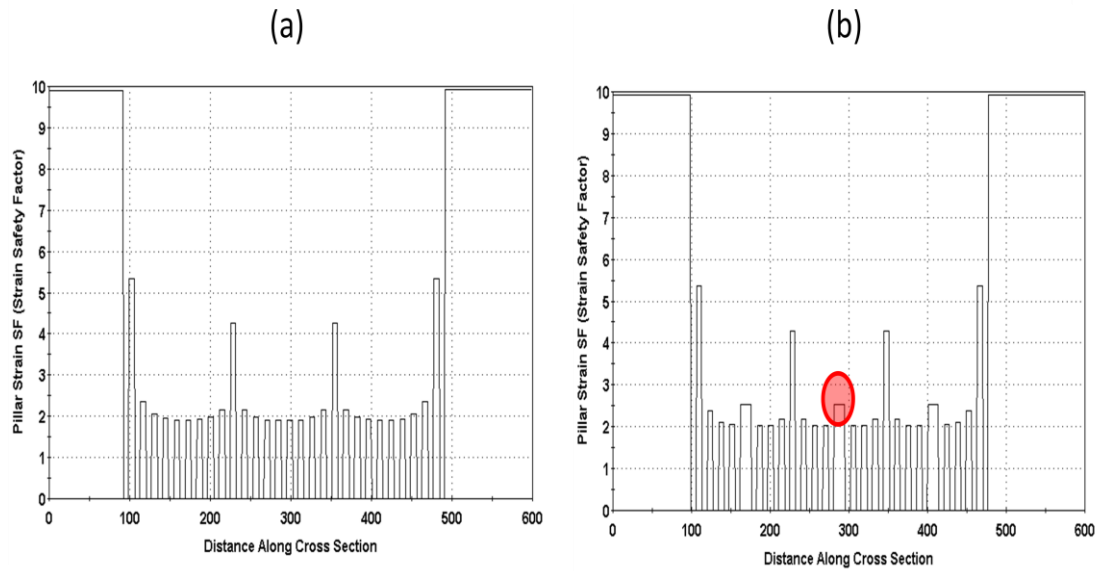


Figure 5.18: Illustration of change in safety factor as a result of combining the pillars at the centre of the panel

It is possible in this option to apply the findings of design option 1, i.e. the final layout may have smaller P1 pillars adjacent to barrier pillars and larger centre panel pillars. In this regard, extraction is optimized under stable conditions.

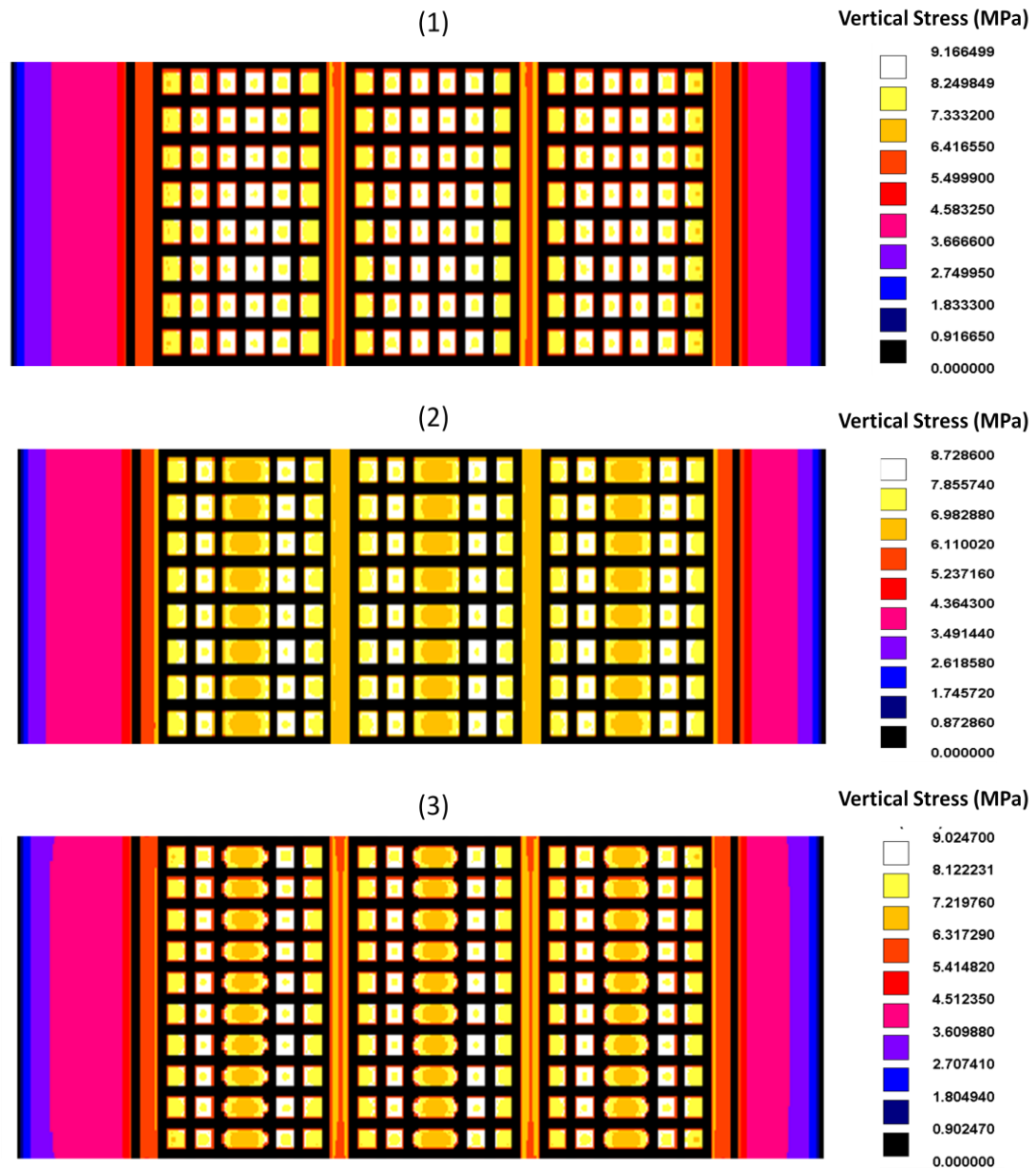


Figure 5.19 Total vertical stress square plot for the model at 150m depth

In figure 5.19 above, combining the centre pillars (2) shows that overall vertical stresses on the panel will be less than for the original design panel (1). The new centre pillars when reduced in an optimizing procedure result in a panel that still has

less vertical stresses (3). When the bords between the centre pillars are increased by reducing the size of the centre pillars, vertical stresses increase.

Figure 5.20 compares seam convergence across and along the panel for original design (a) and design 1.2 (b). Application of the new design shows that seam convergence will be slightly lower than that of the original design.

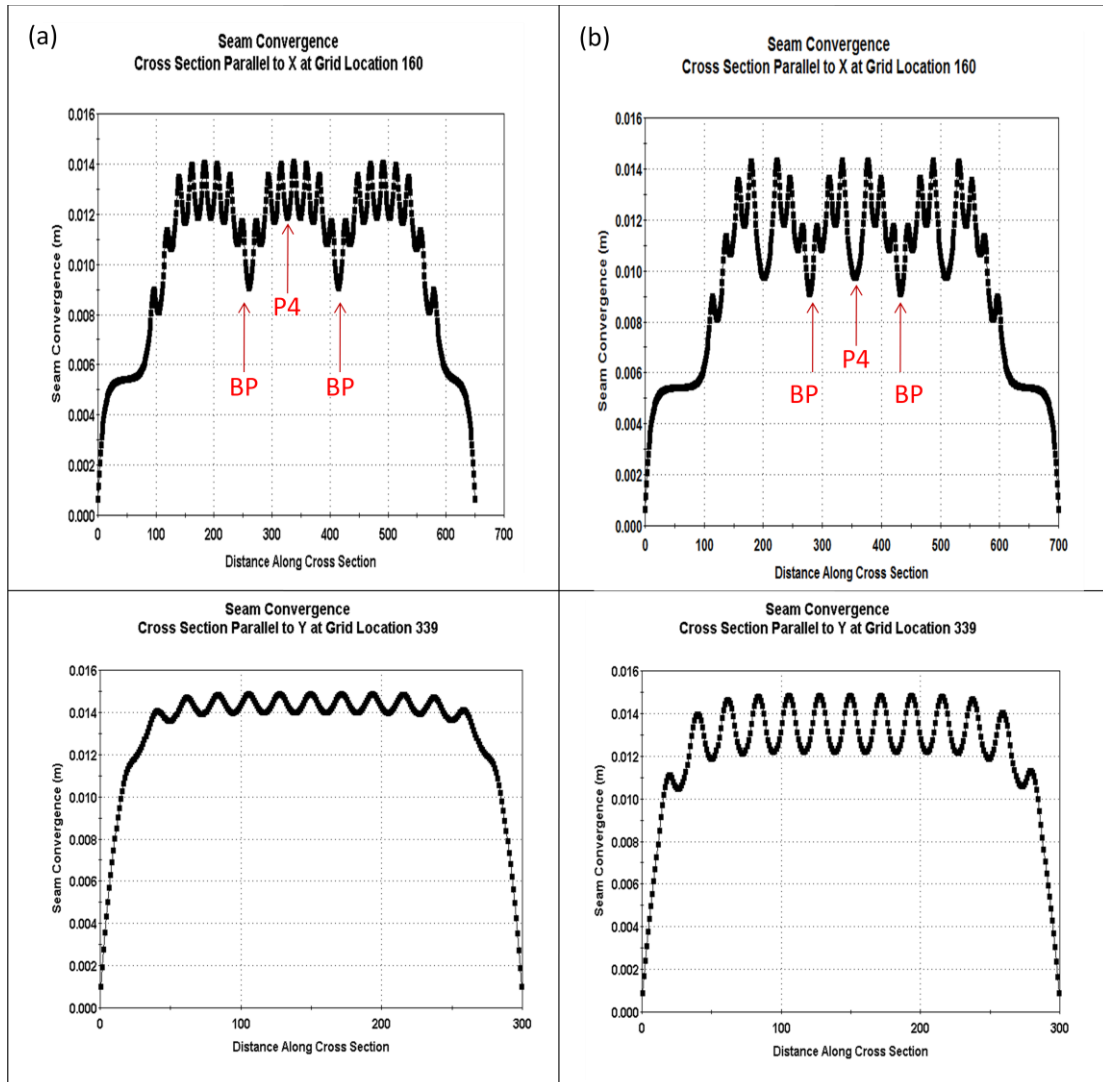


Figure 5.20: Seam convergence comparison between (a) original design and (b) design 2.1 across and along the panel at 150m depth.

In option 2.1 the panel centre will be more stable and resource utilization will be increased (percentage increase in centre pillars can be up to 6.7%). However since the belt road will not be at the centre of the panel, one portion of the mine will advance much faster than the other, and this may affect operational efficiency.

Figure 5.21 shows the relationship between overall extraction and the panel centre pillar for panels at different depths.

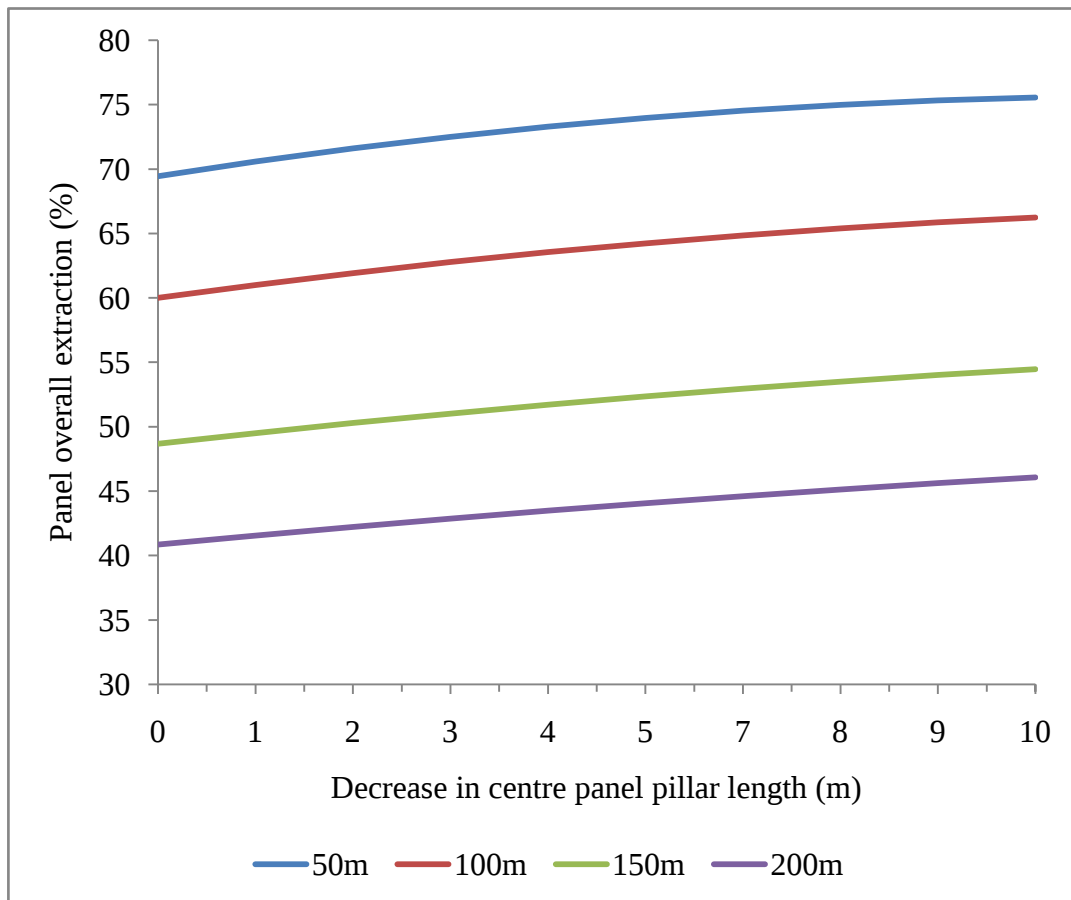


Figure 5.21: Relationship between overall extraction and centre panel pillar length at different depths

For a panel at 50m depth, to achieve improved extraction as compared to the original design, the central pillar should measure 18m by 7m at most (figure 5.22), or should have an effective width of 10.1m

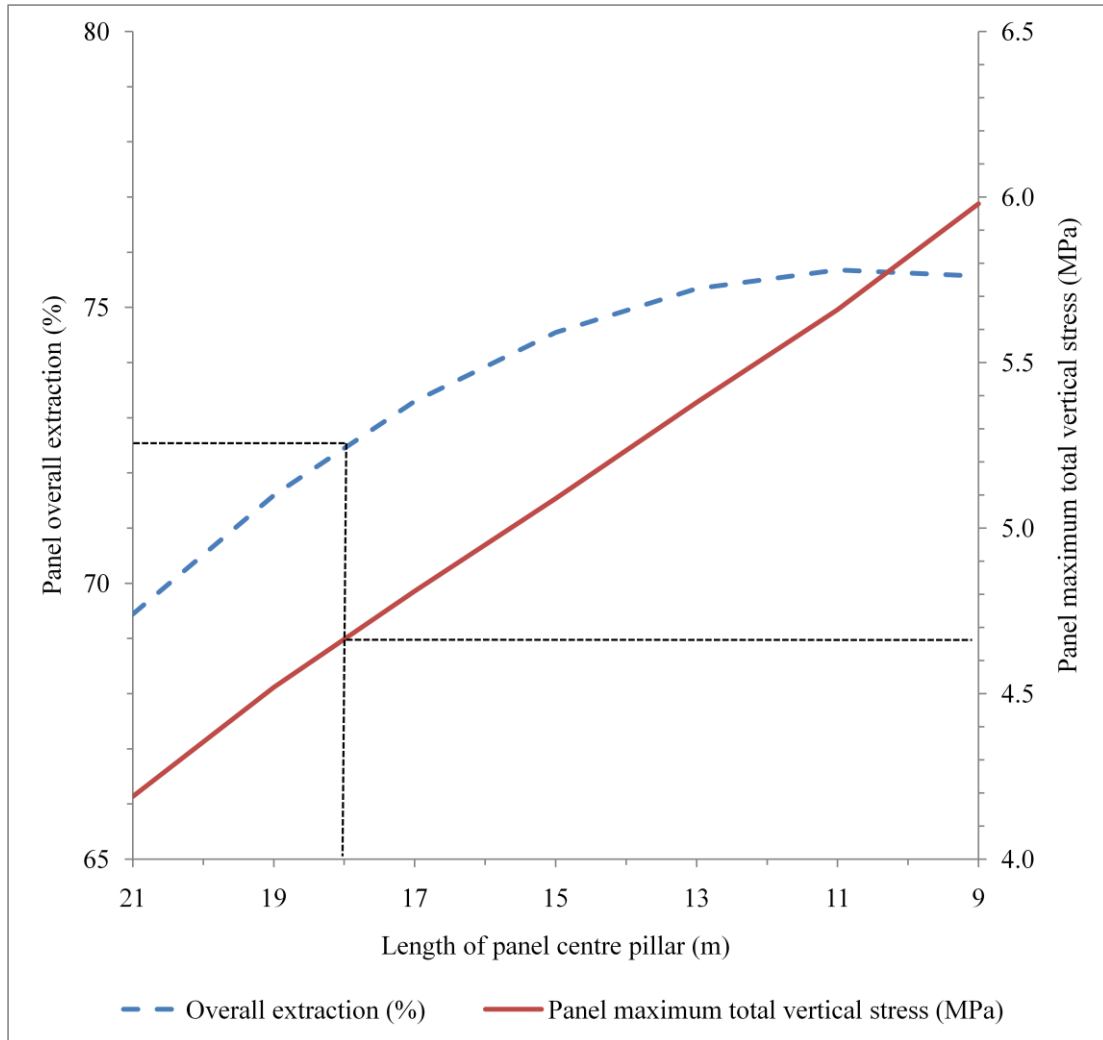


Figure 5.22: Panel overall extraction variation with maximum total vertical stress at 50m depth

An extra 2.5% in central pillar areal extraction (resulting in about 0.2% increase in overall extraction) can be gained without significantly affecting the panel's maximum

total vertical stress. Pillar safety factor comparison shows an improvement in the overall stability of the panel (Figure 5.23).

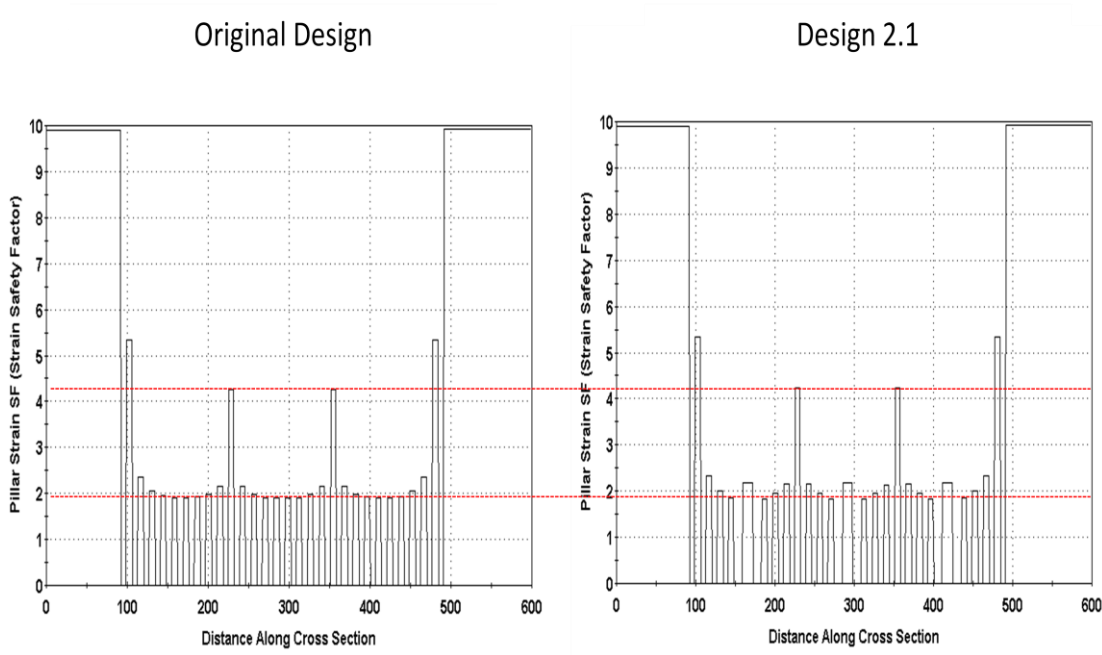


Figure 5.23: Safety factor comparison at 50m depth

Table 5.3 gives a summary for design option 2.1 for various depths.

Table 5.3: Summary of design option 2.1 parameters

Depth	50m	100m	150m	200m
Pillar area (m ²)	49	100	225	400
Combined centre pillar area (m ²)	147	249	555	940
Minimum area to be mined from new centre pillar to maintain recovery (m ²)	49	70	105	140
Effective centre pillar area (m ²)	98	179	450	800
Effective centre pillar width (m)	9.9	13.4	21.2	28.3
Pillar original areal extraction (%)	75.0	65.4	53.5	45.1
Overall areal extraction (%) - original	72.22	62.71	50.41	41.29
Overall areal extraction (%) – design 2.1	72.40	63.09	50.86	41.84
Increase in panel overall extraction (%)	0.20	0.38	0.44	0.55

5.4.2 Design option 2.2

Design option 2.2 focuses on reducing the road width at the centre of the panel, this increases the safety factor of the centre pillars which are then subsequently sliced to increase recovery.

In figure 5.24 below, the five 7m roadway panel at 200m depth is compared to a similar panel but having a 5m roadway at the centre (belt drive). Thus 40m^2 of area is left in the two adjacent pillars at the centre of the panel. The maximum total vertical stress is reduced by 1.7%. To regain this tonnage the central pillars are sliced, giving the geometry shown in figure 5.25. Figure 5.26 illustrates the increase in panel overall extraction for different depths. A comparison of the distribution of the Lamodel vertical stresses between the two designs is shown in figure 5.27.

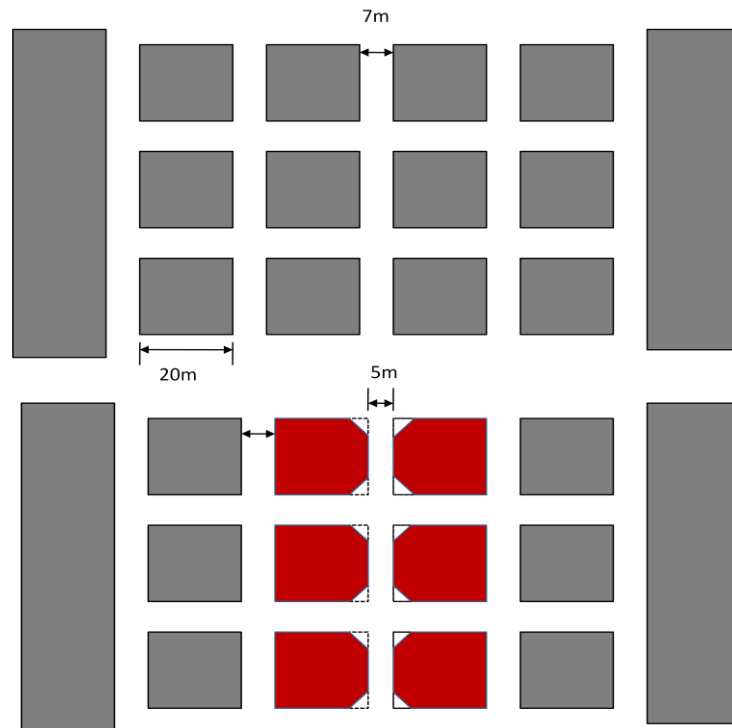


Figure 5.24: Illustration of the design option 2.2 concept

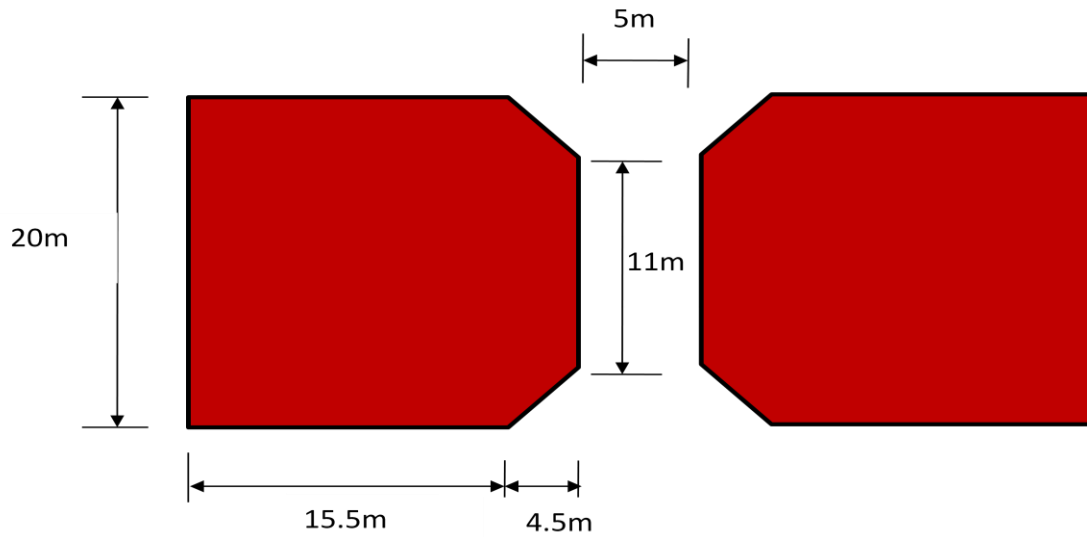


Figure 5.25: Arrangement of central pillars for design option 2.2 at 200m depth

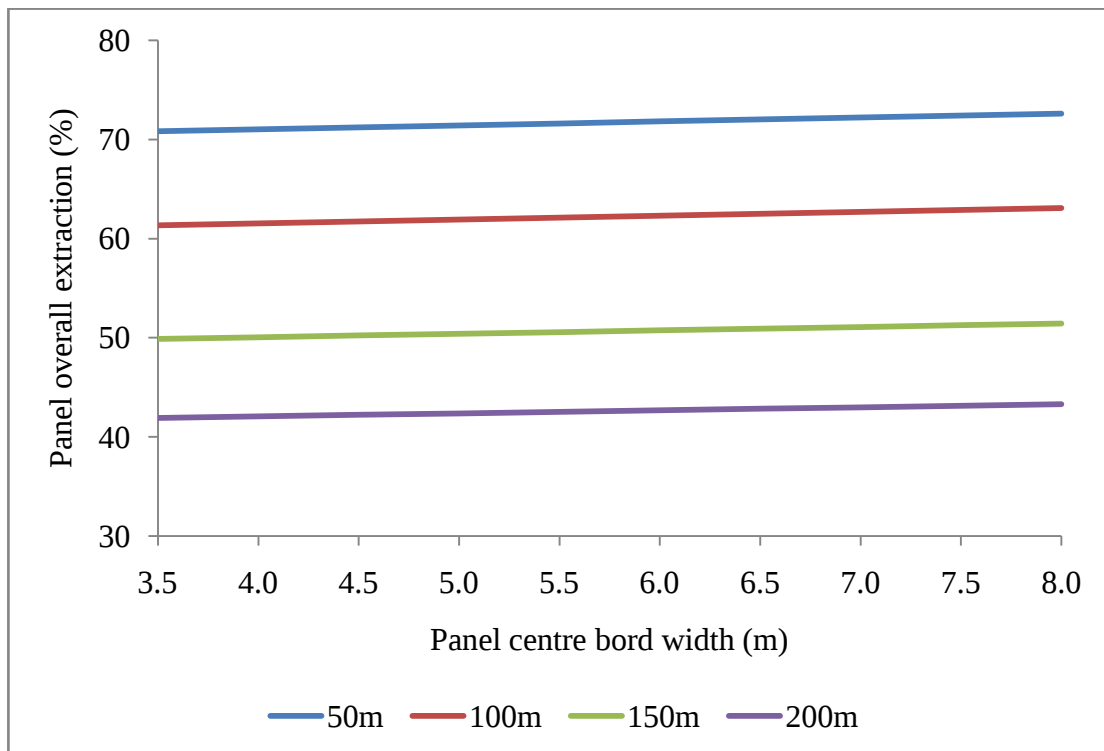


Figure 5.26: Panel overall extraction variation with increase in panel centre bord width

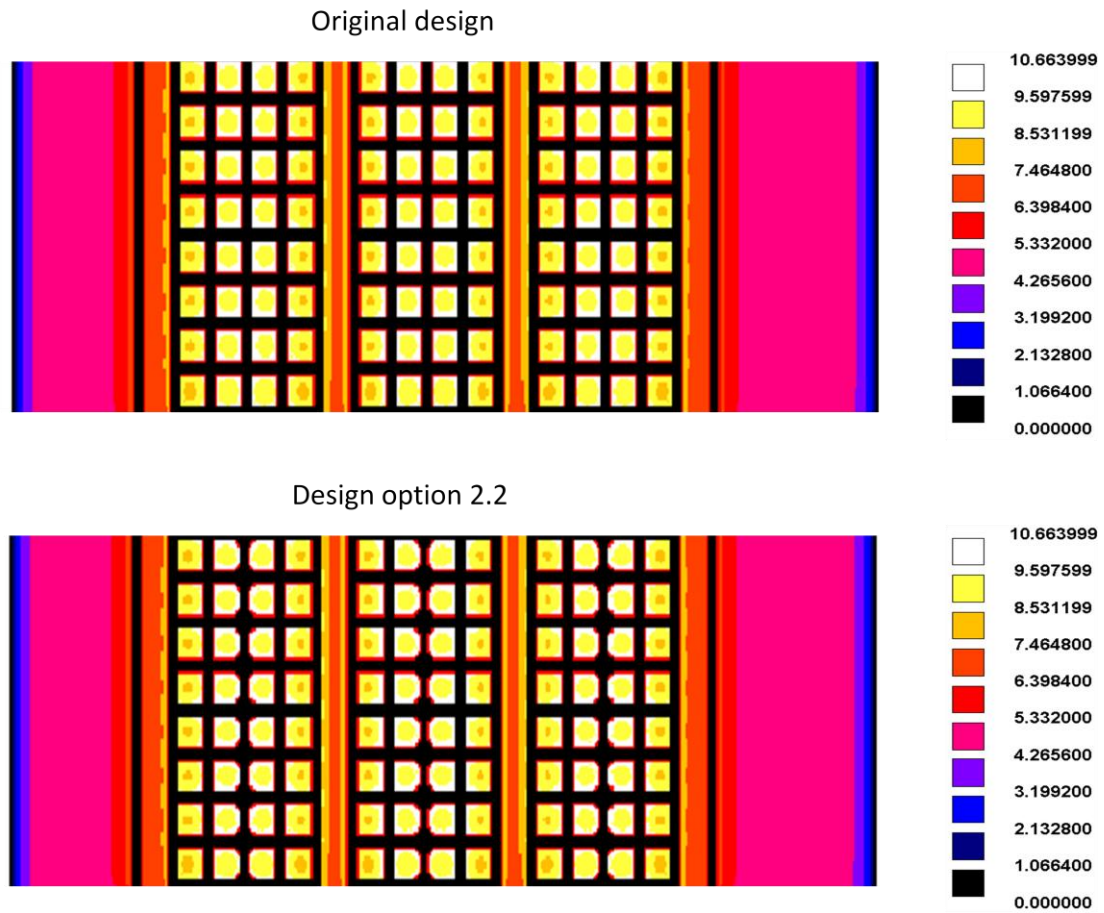


Figure 5.27: Vertical stress distribution at 200m depth for original and option 2.2 designs

It is interesting to note that in this optimized design the vertical stresses are exactly the same for both cases. However in design option 2.2 an extra area of about 0.5m^2 is available for extraction, this equates to an effective areal extraction of 47.9% which is 2.8% higher than that for the original design. To achieve this extraction, the width of diagonals at the intersection can be increased by 4.8% without potential roof fall hazards.

Whilst the vertical stresses are similar, seam convergence (Figure 5.28) at the intersections for design option 2.2 are slightly higher by up to 2.1% than for the original design. This is due to the increased width of the diagonals at the intersections.

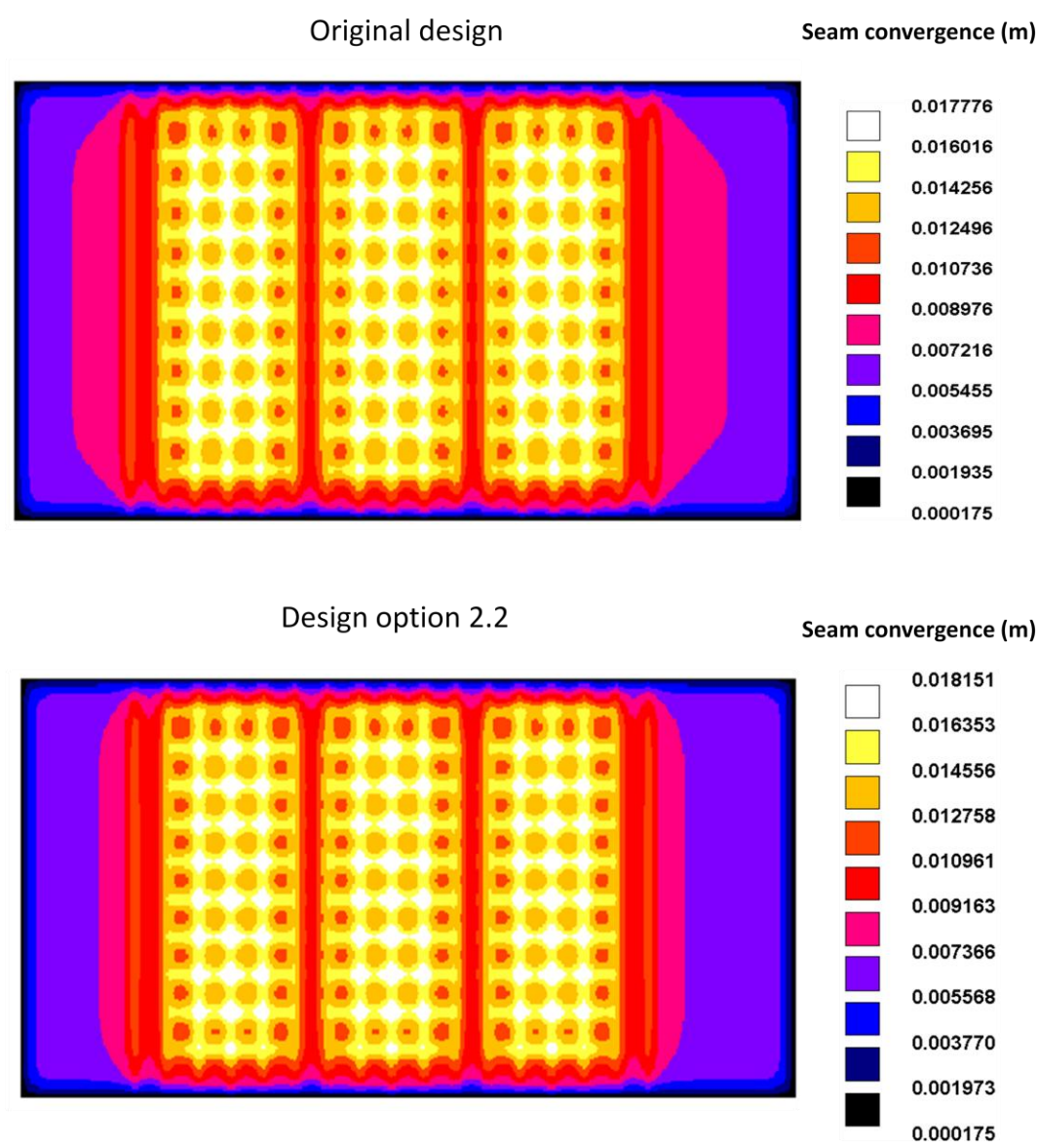


Figure 5.28: Seam convergence at 200m depth

Table 5.4: Summary of design option 2.2 parameters

Depth	50m	100m	150m	200m
Pillar area (m ²)	49	100	225	400
Combined centre pillar area (m ²)	147	249	555	940
Bord width between in-panel pillars (m)	7	7	7	7
Bord width between centre pillars (m)	5	5	5	5
Areal extraction (%) - original	75.0	65.4	53.5	45.1
Overall areal extraction (%) - original	72.22	62.71	50.41	41.29
Overall areal extraction (%) – new design	72.45	63.07	50.85	41.84
Increase in panel overall extraction (%)	0.25	0.36	0.43	0.55

5.5 Design option 3: Barrier pillar pocketing

The basis for this design option is the fact that barrier pillars are at lower stresses than in-panel pillars, hence they can be slightly ‘robbed’ without having much effect on the overall stability. Focus will then be where exactly the barrier pillars should be partially extracted. Figure 5.29 shows the distribution of vertical stress for two cross sections cutting across barrier pillars, one is across in-panel pillars ($Y = 140$) and the other is across the crosscut ($y = 173$). The results indicate negligible variation in vertical stress, and the same holds for safety factor (see figure 5.30).

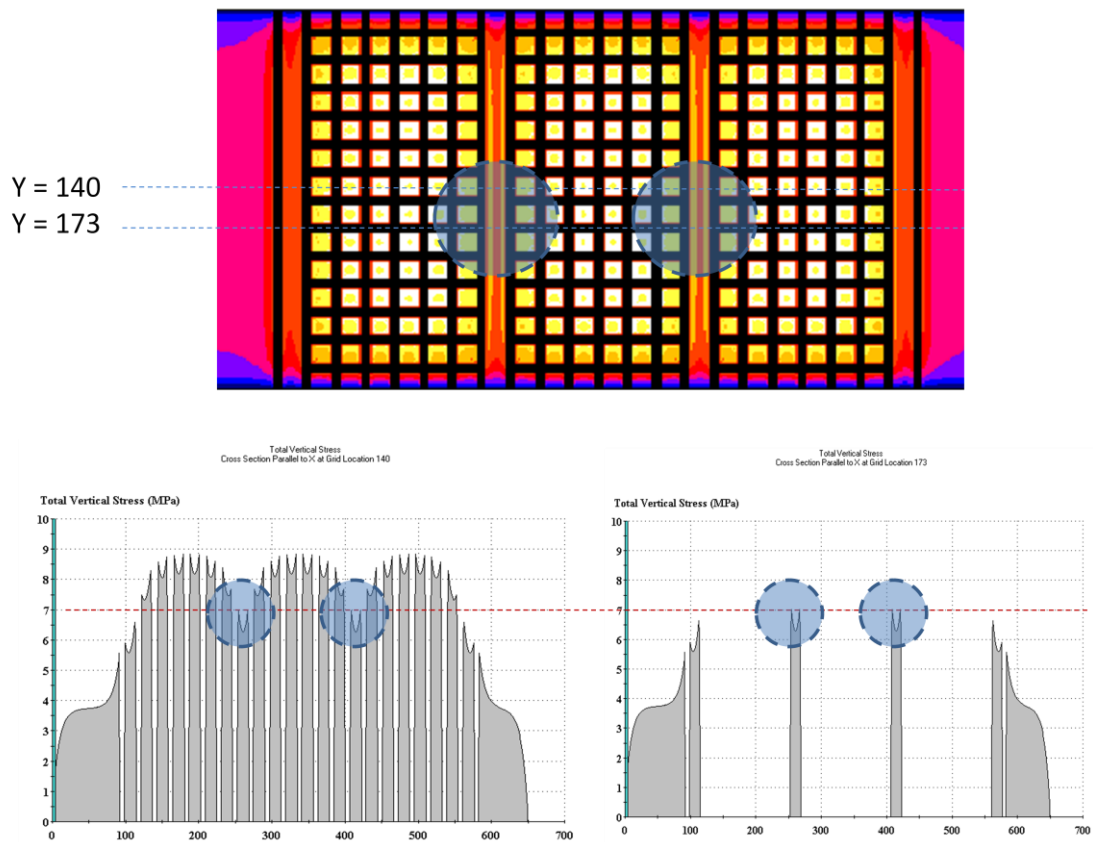


Figure 5.29: Distribution of vertical stress across a 7 roadway panel

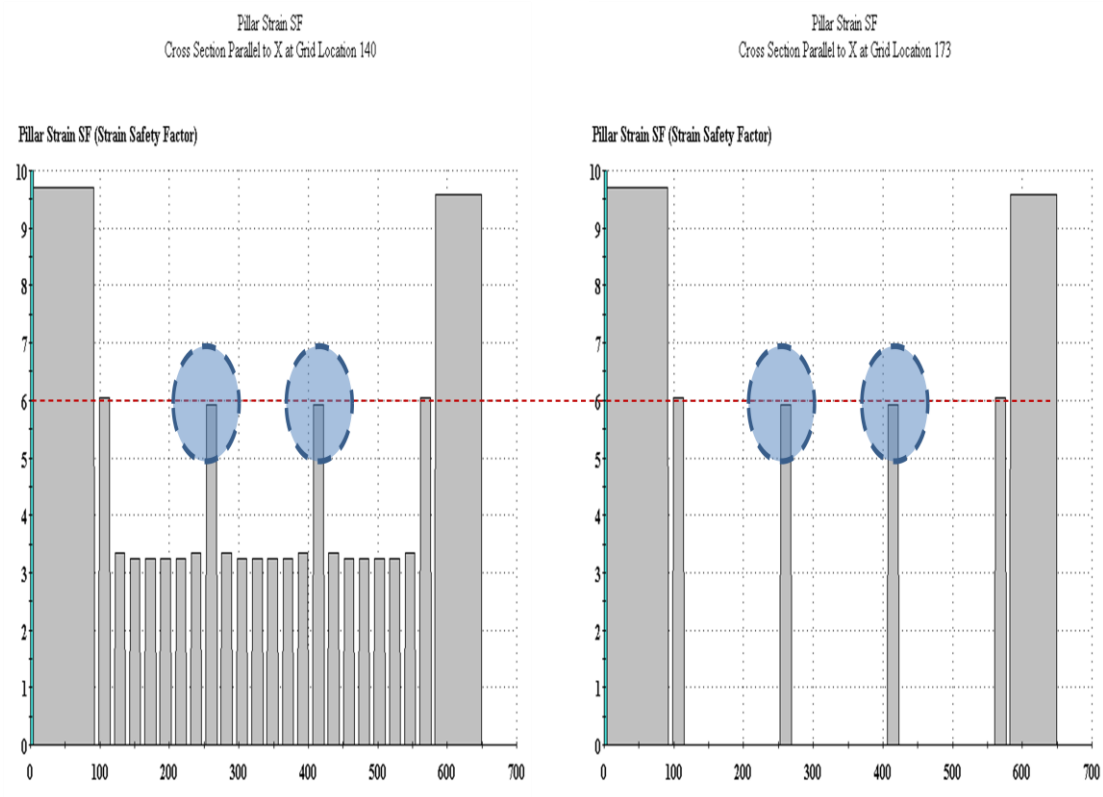


Figure 5.30: Safety factor distribution

These findings may mean that partial extraction can be done anywhere along the barrier pillar. Figure 5.31 shows two ways in which this option may be implemented. The difference in the panel maximum total vertical stress is minimal (0.0017MPa).

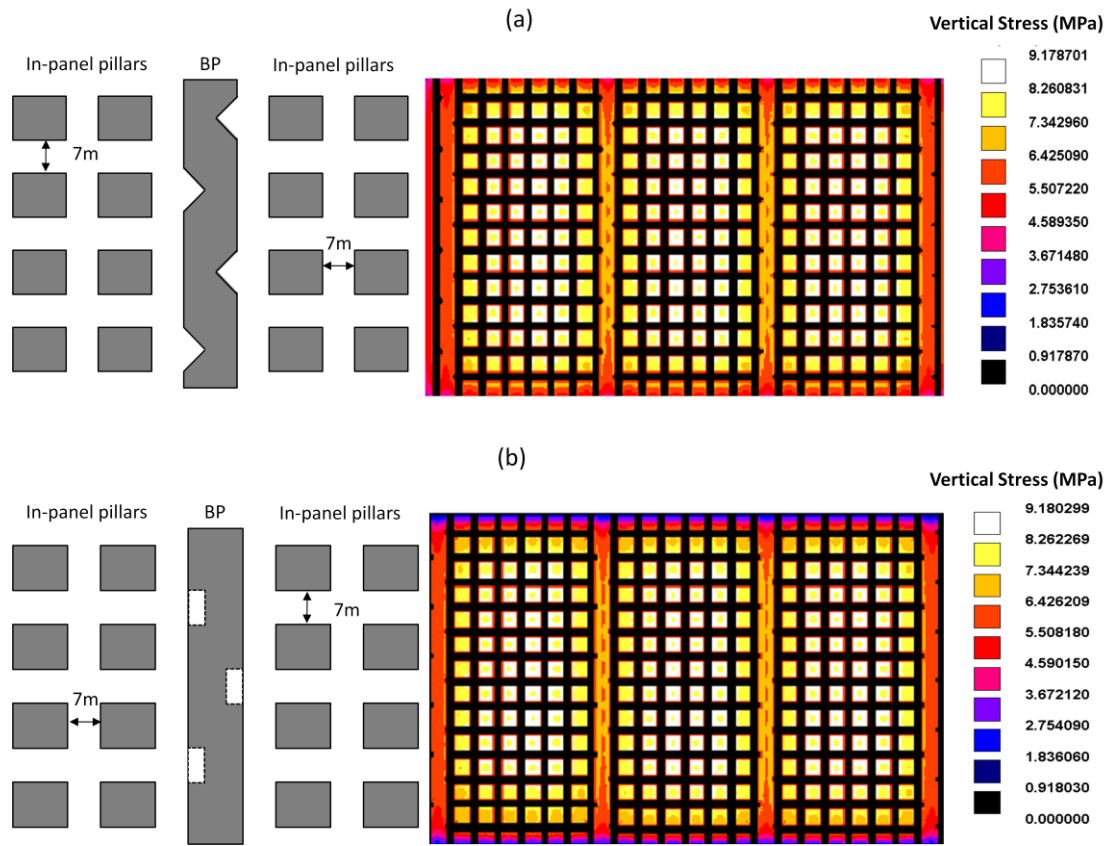


Figure 5.31: Illustration of two possible methods of barrier pillar pocketing at 150m depth

In the analysis of the above configurations about 6.5m^2 is extracted from both the barrier pillars in (a) and (b). For the same areal extraction, option (b) gives slightly higher stresses. In terms of productivity, (b) offers a higher operational efficiency than (a) as less time is spent on setting up the machines for the cuts.

Table 5.5: Summary of design option 3 parameters

Depth	50m	100m	150m	200m
Barrier pillar width (m)	7	10	15	20
Area extracted from barrier pillar	45	97.75	224	399.75
Overall areal extraction (%) - original	72.22	62.71	50.41	41.29
Overall areal extraction (%) – new design	72.56	63.30	51.19	42.17
Increase in panel overall extraction (%)	0.34	0.59	0.78	0.88

5.6 Productivity and safety considerations

While the methods presented in the previous subsections are aimed at improving a panel's extraction, the rate at which the extraction is done (productivity) may be lower than that for the current designs. If pillars across a panel are not uniform, the mining sequence may become complex for the miner. This may result in extra time being taken in relocating and setting up the machines for the splits and in so doing chances of electric cable and equipment damage will be high. Further to this, the CM operators will have to know which pillars have which dimensions in each of the rows in a panel to avoid over cutting of pillars which may result in reduced safety factors.

5.7 Summary

Table 5.6 and figure 5.32 present a summary of the alternative design options discussed.

Table 5.6: Summary of design options

Design option	Brief Description	Sub-options	Improvement in panel overall extraction (%) at different depths			
			50m	100m	150m	200m
1	P1 pillar size reduction	1.1	0.52	0.32	0.24	0.13
		1.2	0.20	0.13	0.03	0.01
2	Re-sizing of panel centre pillars	2.1	0.20	0.38	0.44	0.55
		2.2	0.25	0.36	0.43	0.55
3	Barrier pillar pocketing	3	0.34	0.59	0.78	0.88

Figure 5.32 show that the extra coal recovered for design options 1.1 and 1.2 decreases with increase in depth. It may be desirable to employ these options when mining panels which are at shallow depths. In contrast, the additional recovery for design options 2.1, 2.2 and 3 increases with depth and they thus can be applied in deep seated seams. Above all, barrier pillar pocketing offers the highest increase in overall panel extraction and can be applied across all depths.

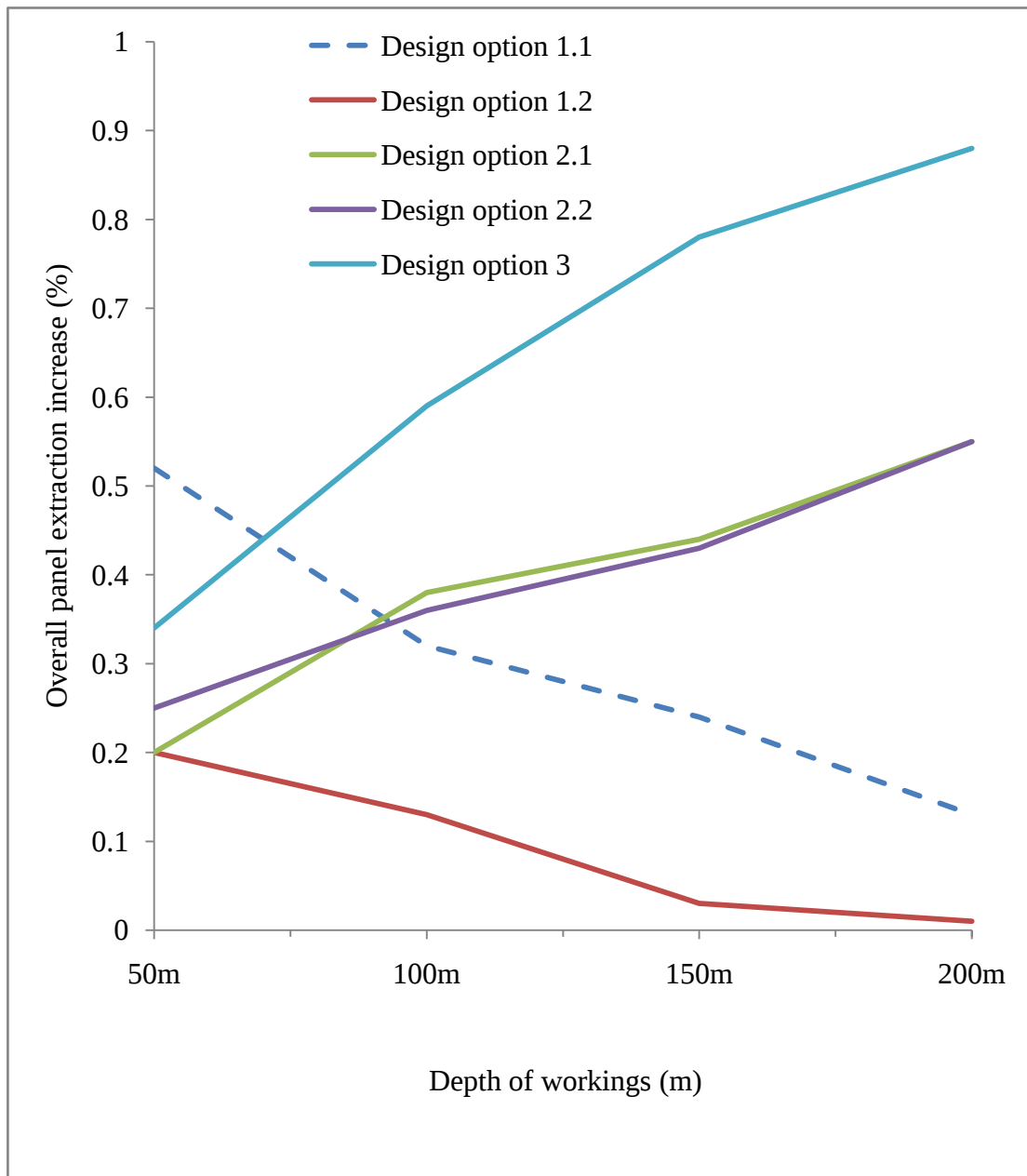


Figure 5.32: Overall panel extraction increase versus depth for different design options

5.8 Conclusion

In this chapter an attempt has been made to take advantage of the non-uniformity of safety factors in panels to improve extraction without significantly impacting on overall stability. It has been shown that it is possible to increase extraction in several ways. While the present designs are easy to apply on the ground, the alternative designs will require mining personnel to undergo training to avoid over cutting of the pillars in question and also to maintain acceptable productivity levels.

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

The understanding of the interaction between barrier pillar and in-panel pillars in bord and pillar mining is essential when considering designs for optimized extraction. The objective of this study was to gain an understanding of the influence of the barrier pillars on the stability of in-panel pillars in bord and pillar panels, so that layout designs can consider improved extraction whilst maintaining panel stability. The objective has been achieved by:

- A review of the coal pillar empirical design methodology in which it is noted that the designs do not take into account the unequal distribution of stresses on pillars across a panel.
- Numerical investigations into the loading of barrier and in-panel pillars at different depth using the Lamodel software package. All models investigated indicated that pillars close to barrier pillars carry less stress and have higher safety factors than the rest of the pillars in the panel.
- Underground investigations to validate the outcome of the initial numerical investigations through observation and measurement of pillar scaling at a coal mine. Centre pillars in a panel indicated higher scaling rates than those next to barrier pillars, a possible indication of higher stresses in the middle of a panel.

Based on the above, detailed numerical analysis of the effects of reducing the size of pillars closer to barrier pillars, repositioning of centre pillars and barrier pillar

pocketing has been conducted. The results of modeling suggest that there is potential to increase extraction in the current bord and pillar primary extraction layout designs without affecting overall stability.

Increasing the width of barrier pillars enhances the stability of a panel at the expense of extraction. Further to this, it is noted that the size of the barrier pillar cannot be increased for reduced in-panel pillar size if production has to be improved. However, if extraction is to be optimized without affecting the stability of workings, the lower stresses carried by pillars closer to the barrier pillars can be taken advantage of by slightly reducing their size in comparison with the other pillars. The increase in overall extraction from current extraction techniques is between 0.01% and 0.5%, depending on the depth of the resource and layout configurations. In essence, this means a coal resource having 1bnt mineable reserve may realise an additional tonnage of up to five million tonnes. This technique maybe favourable for panels at lower depths.

Pillars at the middle of the panel have shown to have higher stresses and low safety factors than those close to barrier pillars. By reducing the number of bords at the expense of combined centre panel pillars the overall stability of the centre panel can be improved. The new central pillar can be partially extracted to compensate for the loss due to the removal of a single roadway. This technique is particularly suited for larger pillars at greater depths. Additional panel recovery ranges from 0.20% to 0.55%.

Another method of improving extraction is to consider the high safety factor exhibited by barrier pillars. Numerical modelling has shown that it is possible to partially extract the barrier pillars by small amounts at appropriate positions along them. This increases extraction by between 0.34% and 0.88% and suits all deposits at various depths.

6.2 Recommendations

In view of the potential benefits of applying the findings of this research, the following recommendations are made:

- Practical implementation of the research findings, which in the long term and through the same statistical analysis as conducted by Salamon (1967) and Madden (1990), may possibly lead to new pillar design equations that take into account the unequal distribution of stress across a panel.
- Monitoring of roof convergence to ensure stability of the increased bords in the new methods.
- Re-assessment of bord and pillar mining equipment designs (continuous miner, shuttle cars and roof bolter) to suit the new proposed layouts.
- Advanced training for mining personnel and machine operators with the aim of maintaining or improving productivity.

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Appendix: Historical Barrier Pillar Design Formulae

Source: The Hydraulic Design of coal barrier pillars (Rangasamy et al, 2001).

Method	Formulae	Comment
Dunn's method (1846)	$W = \{(D - 180) / 20\} + 15$ Where W = barrier pillar width (ft) and D = depth of mining cover (ft)	Dunn's rule gives undersized barrier pillar dimensions for given mining depths and does not account for the effects of seam thickness.
Pennsylvania Mine Inspector's Equation	$W = 20 + 4T + 0.1D$ Where D = depth of mining cover, or height of hydrostatic head if greater than thickness of overburden, rounded up to the nearest 100ft.	The equation takes into account of the thickness of the coal seam. Because it also allows incorporating the water pressure, it became a candidate equation for the design of water barrier pillars.
Ash and Eaton Impoundment Equation (1948)	$W = 50 + 0.426D$ Where D = depth of mining cover (ft)	The equation gives extremely conservative barrier pillar sizes for a given depth of mining and does not consider the effects of coal seam thickness and strength.

The North American Method	$W = \frac{(D \times P)}{7000 - D}$ Where P = width of adjacent panel (ft), and D = depth (ft)	This method is similar to the pressure arch method employed in Europe and it includes the effect of variations in adjacent pillars at great depths. The effects of coal strength and water pressure are ignored.
Outcrop water barrier pillar - Kentucky	$W = 50 + H$ Where H = elevation of water impounded	The equation ignores the beneficial effects of stress on pillars, and would require extremely wide pillars, with widths equal to the water head (plus 50ft).
Old English Barrier Pillar Law	$W = \frac{HT}{100} + 5T$ Where H = hydrostatic head or depth below drainage level (ft), and T = coal seam thickness (ft)	The use of the equation should be avoided for the design of barrier pillars whose intended function is other than that of an impoundment dam. The reason is that, if no water pressure exists, the equation determines the same barrier pillar width for all mining depths. The rule also ignores the effect of coal strength.

Pressure Arch Method	$A = 3 \left(\frac{D}{20} + 20 \right)$ <i>A= minimum width of maximum pressure arch from which the proper panel and barrier pillar width maybe calculated.</i>	The method is not appropriate for overburden depths of less than 400ft or greater than 2800ft.
British Coal Rule of Thumb (1971)	$W = \left(\frac{D}{10} \right) + 45$	The rule does not account for variations in coal seam thickness and strength.
Holland Convergence method (1973)	The width W should be larger of: $W = 15T$ Or $W = \frac{5(\log 50.8C)}{E \log e}$ <i>Where C= estimated convergence on high-stress side of barrier pillar (in), E= coefficient of extraction adjacent to barrier pillar, e=base of the natural system of logarithm, T=seam thickness</i>	The rule is based on field data from specific coal mining region of Europe and requires appropriate engineering judgement.