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WITWATERSRAND,
JOHANNESBURG

MSc (Eng) RESEARCH REPORT

**Pillar stability analysis from secondary extraction at Goedehoop
Colliery's No.2 Seam**

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2018

Declaration

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

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Abstract

The current outlook for coal within the global energy market compels South African based collieries to re-strategize their current methods of extraction, with the decline of coal reserves within the Witbank coalfield. An economically feasible alternative would be secondary extraction methods that are relatively low in financial and safety risk. However, efficient mining can only occur where optimal rock engineering practices are used.

The No. 2 Seam (thickness of about 6m) has always been a favoured deposit for extraction within Goedeheop colliery, consisting of 'good quality' economical coal. Where previously mined at about 4.5m, a possible 1.5m remains either in the roof or floor for extraction (when mined in conjunction with the No.1 seam in areas of thin seam parting).

Despite the remaining coal having the potential to be included in future plans, the current concern is the stability of pillars within panels associated with the progressive failure due to minimal roof support and poor rock engineering design, without accounting for the risk of failure. If the failure of the pillars were to occur, it will cause the sterilization of the No.4 seam that is currently being mined above the No. 2 Seam.

A bottom/top coaling case study was looked at Goedeheop colliery with the aim to evaluate the stability of pillars within the panel/s using stability criterions (Factor of Safety, Probability of Failure and Probability of Survival). Using the pressure arch theory and applicable strength equations to the No.2 seam, the stability of individual pillars was evaluated, where previously coaling had taken place. The results estimated the likelihood of failure of the pillars within the selected panel. The results from the study showed that if and where coaling has taken place it is likely that the pillars would remain stable well above the FOS value limit of 1.6 and resides within the 99% POS limit of production panels.

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Nomenclature

C2C - Centre to centre

FOS/SF - Factor of Safety

GRC - Ground Response Curve

k - Ratio of horizontal to vertical stress

K_M - Stiffness of the system

K_p - Post-failure stiffness of the support structure

L.O.M - Life of mine

MPa - MegaPascal

Mt - Million tonnes

No. - Number

σ_v - Overburden stress

OECD - Organisation for Economic Co-operation and Development

PAT – Pressure Arch Theory

POF - Probability of failure

POS - Probability of survival

Psi - Pounds per square inch

R.O.M - Run of Mine

TAT- Tributary Area Theory

W/h - width to height ratio

Chapter 1: Introduction

1.1 Introduction

The depleting coal reserves in the Witbank coalfield are expected to last for approximately 15-25 years (Chabedi, 2013). This was based on an assumed annual tonnage of 200-250 Mt of Run-Of-Mine (ROM) extracted from the coalfield. Of the estimated coal reserves in South Africa, more than half of the annual run-of-mine is produced solely from the Witbank coalfield (Prevost, 2011).

Coal has remained the primary energy resource, providing for 41% of the global energy requirements and an even higher percentage by developing countries (non-Organisation for Economic Co-operation and Development members) (World Coal Association, 2017). Not to mention, analysts have forecasted that the demand for energy is expected to increase by 56% in the next 23 years (Energy Information Administration, 2013). With an emphasis on the global energy demand increase and the local known resources dwindling concurrently, other potential reserves within the Witbank coalfield are explored.

Secondary extraction methods provide an alternative solution to increased reserves, which will not only extend the Life-Of-Mine (LOM) of Witbank collieries but above all eliminate the financial burden of capitalisation of new mines. The choice of mining method depends on the economic, financial, health and safety risk affecting the mine/s and their surrounding communities (Lind, 2005).

Of the numerous secondary extraction methods that have been applied to the coal industry, bottom or top coaling (extraction of coal roof or floor) was considered, specific to the No.2 Seam to allow full utilisation of the remaining coal. This was based off the quality of the coal and on the assumption that an average extraction of 50% was maintained in the Witbank coalfield, using bord and pillar mining. The aforementioned implies that 25% exists for extraction (Chabedi, 2013), residing in the 75% extraction limit suggested by Madden (1998). Apart from that, coaling is one of the lowest risk secondary extraction methods as compared to stooping, that

can be applied to old working areas to achieve the quality of coal required of economic value (Malogwa, 2017). However, the choices were not limited to bottom/top coaling only.

Optimal secondary extraction can be achieved by reviewing the geotechnical design principles and its effect on the methods chosen for secondary extraction, particularly of pillars. This would ensure that working areas consist of effective support systems that meet their functional objectives, especially since secondary extraction was not considered for final extraction in the Witbank coalfield (Jeffrey, 2002).

1.2 Problem statement

Prior to 1998, the No. 2 Seam was extracted to a mining height of 4.5m, between the top coal and floor coal which is known as the Select 2 zone, depicted in Figure 1.2-1, due to its high quality (Malogwa, 2017). In areas where the Select 2 zone (refers to the preferred area chosen at the No. 2 Seam for extraction) reached 4.5m, the entire portion of the seam was mined. Considering that the No. 2 Seam has been the favoured seam for mining, using bord and pillar mining, with an average thickness of 6m, a significant portion exists either in the roof or floor for extraction (when mined in conjunction with the No.1 seam, in areas of thin seam parting). The remaining coal, in the No. 2 Seam, has the potential to be included in future plans, owing to higher yields and favourable geological conditions

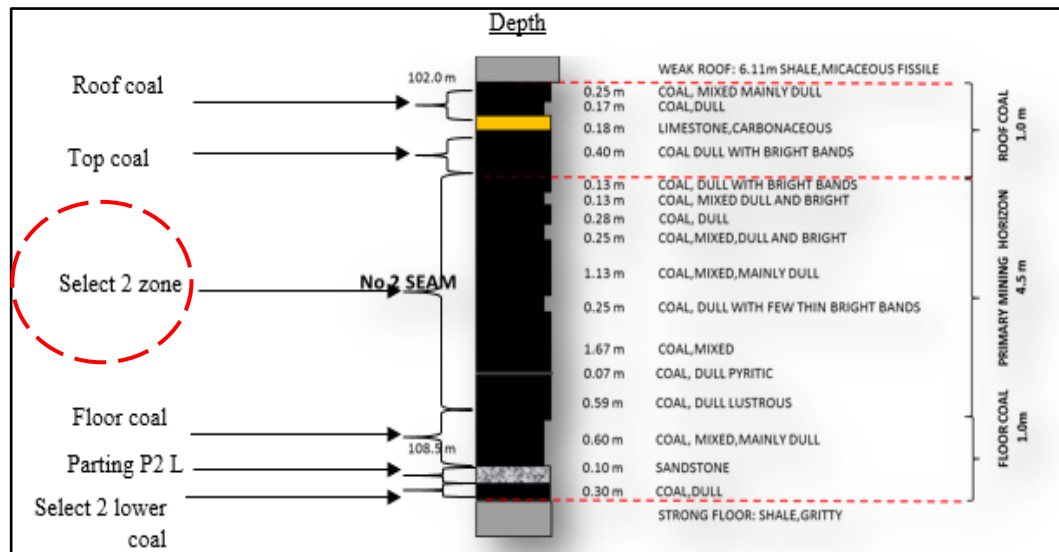


Figure 1.2-1-Stratigraphy column of the No.2 Seam (*AngloAmerican (Thermal Coal), 2015*)

However, due to the lack of rock engineering guidelines available, during the primary extraction of the No. 2 Seam, the majority of the panels were developed without accounting for the risk of failure. The repercussion was minimal roof support within panels and the pillars were developed with the immediate focus on achieving production targets. This left a substantial portion of the pillars in the panels, with a Factor of Safety (FOS) lower than the mining standard of 1.6, which ensures both safe and economic mining, at the depth below surface of the coal seams at Goedehoop colliery (Salamon & Munro, 1967).

Despite the pillars being developed with a safety factor lower than the preferred mining standard, they remain stable. More importantly, if failure were to occur, it would cause the sterilization of the No.4 seam, which is currently being mined above the No.2 Seam.

1.3 The aim of the study

The primary objective of this research is to evaluate potential pillar stability within the No. 2 Seam, where coaling would take place in old workings. This will be achieved by addressing the following objectives:

1.3.1 Objectives

- I. Review the current design practices of pillar design used in the global coal industry and their applicability to the current mine layout at the No. 2 Seam. This includes the design practices used for bottom or top coaling;
- II. Determine the pillar loads where coaling took place using an alternative empirical method, the pressure arch theory and compare the estimated values to the value of the tributary arch theory;
- III. Determine the pillar strength at the maximum height extracted in a panel where coaling took place using empirical strength equations specific to the No. 2 Seam,
- IV. Predict the limits of stability using the Factor of Safety, Probaility of Failure and Probability of Survival for the panel reviewed;

1.4 Limitation of the study

Access to the entire No. 2 Seam is limited because of unsupported roof sections, with only a small percentage of the area being accessible. Therefore, assumptions used to calculate results were based on the currently available data in the digital mine plans provided.

1.5 Content of research

This report was subdivided into 6 chapters. The first, as discussed above, provides the basis of the project. The second chapter is an extensive literature review which looked at research pertaining to underground coal pillar design, aimed at establishing the possibility of stability of pillars at the No.2 Seam. The third chapter entails a detailed mining history of the area looked at in relation to its location, mining method and coaling experience. This is followed by chapter four, which reviewed the methodology taken to determine pillar loads and pillar strength using the pressure arch theory, tributary area theory and the respective pillar strength equations applicable to the No. 2 seam that would be used to assess pillar stability at the No. 2 Seam. This was followed by chapter five that discusses the results obtained from the empirical study from the different theories and formulae. The

report was concluded by chapter six, with conclusions and recommendations for future research.

Any details of additional literature that the reader can further look at related to pillar design from the information collected throughout the research, has been summarized in the Appendices.

Chapter 2: A review of pillar design in coal mining

2.1 Introduction

Coaling entails the extraction of either the coal roof (top coaling) or floor (bottom coaling) within worked areas, in the form of slices. In practical mining application, bottom coaling is favoured over top coaling, especially in thicker seams as it requires less drivage and potentially less roof support (Galvin, 2016). Problems associated with coaling include the progressive change in pillar stiffness, which is caused by the reduction in a pillars' loading capacity (i.e. stiffness) as its height increases through coaling (Galvin, 2016).

This chapter will critically review publications related to underground coal pillar design, with the purpose of understanding the geotechnical considerations, which are related to bottom or top coaling at the No.2 seam. These considerations provide insight into the applicability and limitations of empirical, analytical and numerical theories associated with coaling.

The objectives of the literature review will be achieved by the following sections:

- A review of pillar design;
- Pillar load – Methods used to determine pillar load and their limitations and the influence of the loading environment on the average pillar load;
- Pillar strength – Methods used to determine pillar strength and their limitations;
- Stability criteria used to assess pillar stability.

2.2 A review of pillar design

Pillar design traditionally uses deterministic methods (empirical or analytical) to predict the behaviour of pillars for the first approximation of design (Cauvin, et al., 2005). Through back analysis of collapsed panel cases, the future behaviour of

pillars within a panel is estimated from the past behaviour of a particular data set. All empirical formulae developed are restricted to the empirical range of the parameters considered in the development of the formulas (York, et al., 2000).

The propensity for pillar failure is often amplified as prominent parameters are excluded from the empirical range of pillar formulae, affecting the bearing capacity of the pillars. Ideally, a pillar system designed, would account for all controlling parameters, particularly those that perpetuate failure. These controlling parameters that are likely localised include (York, et al., 2000):

- Geology
- Seam strength
- The rate of loading
- Discontinuities (joints, faults etc.)
- The nature of the surrounding rock strata

Mathey and Van der Merwe (2016), further affirm the concept by asserting that empirical formulae developed are merely guidelines used within support design to determine the average pillar capacity of collapsed cases but do not predict the actual capacity of the individual pillars within a layout.

When using the deterministic method approach, the classical pillar design methodology used in South Africa, as stated by Mark (2006), consists of three steps:

- Estimating the pillar load using the tributary theory (TAT), pressure arch theory (PAT) analytical method, beam deflection theory, photo-elastic analyses and numerical analysis;
- Estimating the pillar strength using the Salamon and Munro pillar strength formula (original and updated), Bieniawski pillar formula, Seam specific formula, Squat pillar formula, Van der Merwe pillar strength formulae (updated) and numerical analysis;

- Calculating the pillar ‘factor of safety’.

The classical approach is quite simplistic, as it ignores the role of site-specific, controlling parameters and excludes the diverse stability criteria available within the rock engineering design of a bord and pillar layout. A re-conceptualisation of the steps considered in pillar design may be required to achieve an effective yet safe mining layout, which meets design objectives and constraints specific to site conditions. York, et al. (2000), summarises the knowledge gaps existing within the current knowledge base in coal pillar design. Some of the knowledge gaps mentioned will be reviewed in this chapter.

2.3 Coal pillar design approaches

2.3.1 Ultimate strength formulations

All, if not most, classical design approaches predict that once the ultimate strength of pillars is reached by the resultant mining stresses, the pillar will fail, having a strength equivalent to zero (Sankar, 2011). This includes the idea that stress across a pillars’ surface area is uniform. The estimation of stability (using the Factor of Safety) in pillar design, using the ultimate strength formulation establishes the strength of the pillar from its geometry, size and the compressive strength of the material.

Roberts, et al. (2005), disproves these formulations, by indicating that a residual strength exists within the post failure of the pillars, caused by self-confinement within the pillar core. Furthermore, if the theory of ultimate strength was, in fact, true, the complete convergence of mine workings would have occurred once the pillar has reached its ultimate strength. Majority of the design approaches discussed throughout this chapter were originally developed using the theory of the ultimate strength of pillars.

2.3.2 Progressive failure formulations

The theory of progressive failure assumes that a non-uniform stress distribution exists within the pillar (Sankar, 2011). The expected behaviour of pillar failure will thus begin at the point of ultimate strength and would gradually progress to ultimate failure.

2.4 Pillar load estimation

2.4.1 Introduction

Upon mining a mineral of economic interest, redistribution of the stresses within the rockmass takes place around the boundary of mine excavations with the intent of achieving a state of stress equilibrium (Yilmaz, 2017). This is either accomplished through the transfer of loads from one pillar to another, increasing the load in one component whilst relieving the load in another or by complete relief through caving (Esterhuizen, et al., 2010). Since caving is prevented during the primary development stage of mining by the pillars which remain, a greater proportion of the overburden load is supported by the pillars. The extent of loading of the pillars is a function of mining-induced stresses, the load transfer mechanism, mining history and surface loading (York, et al., 2000).

Unlike the loading environment, the Average Pillar Load (APL) carried by an individual pillar is designed as a function of the pillar geometry and overburden weight (Esterhuizen, et al., 2010). The significance of the controlling parameters aforementioned, on the magnitude of the APL are neglected throughout most load estimation techniques. By reviewing the parameters, their influence on the bearing capacity of pillars can be assessed.

2.4.2 Factors influencing the pillar load

Background

Statistically derived coal pillar design methodologies suggest that the vertical stress (in the direction of the vertical principal pillar axis) within a continuous bedded

strata remains the same, even if the stiffness of the rock types within the overburden, surrounding strata and pillar vary (Nemcik, et al., 2006). However, as mentioned by Nemcik, et al. (2006), the horizontal stress shares a proportional relationship with a rockmasses stiffness given that each rocktype's elastic modulus differs.

The lateral stress and vertical stress are described by a k-ratio value, that changes depending on the locality of the mine excavation in the rockmass, overburden depth and the presence of stress concentrator's such as dykes, faults, joints, rivers and valleys (Martin & Maybee, 2000). Yet, studies have shown that the value of the lateral stress is 1.5-4 times greater than the vertical stress value initially estimated using the k-ratio (Nemcik, et al., 2006). If the assumption made by Nemcik, et al. (2006), and other derived coal pillar design methodologies were valid, it would only be logical that the lateral stress would remain constant as well, irrespective of the rockmass properties. Since this is not the case, it is possible to argue that the vertical stress would differ depending on the surrounding rockmass and overburden properties, along with the ground response. However, the impacting parameters are not limited to the two aforementioned and would include those mentioned in Section 2.2.

Surrounding strata properties: Overburden and rockmass stiffness

The distribution of stresses surrounding a bord and pillar layout is affected by overburden stiffness, influencing the rockmass ability to absorb greater loads (Nemcik, et al., 2006). Stiffer overburden creates a well-developed pressure arch, evenly distributing the stresses amongst the pillars in a layout, allowing a greater portion of the stress to be carried by abutments, as illustrated in Figure 2.4-1 (Esterhuizen, et al., 2010).

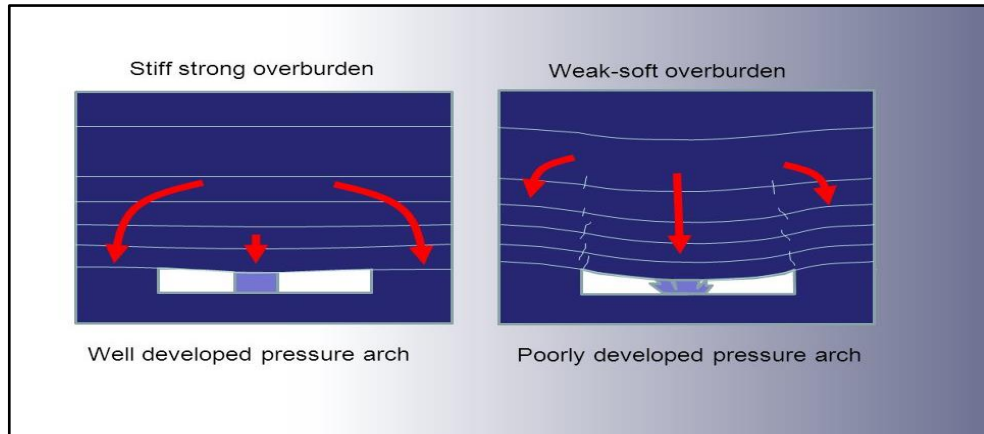


Figure 2.4-1- Depiction of the how the overburden stiffness affects the load carried by a single pillar (*Esterhuizen, et al., 2010*)

When the overburden is soft, a poorly-developed pressure arch is formed increasing the overburden's deflection and the load carried by the individual pillars, depending on their spatial positions within the panel (Hopkins, 1993). The amount of deflection is controlled by either the excavation geometry or the spanning capabilities of the massive strata unit (Mining weekly, 1996). The induced deflection by the overburden layers relieves its load by compressing the pillars, subsequently converging a panel with the accumulation of time. This behaviour is best represented by the ground response curves, depicted in Figure 2.4-2.

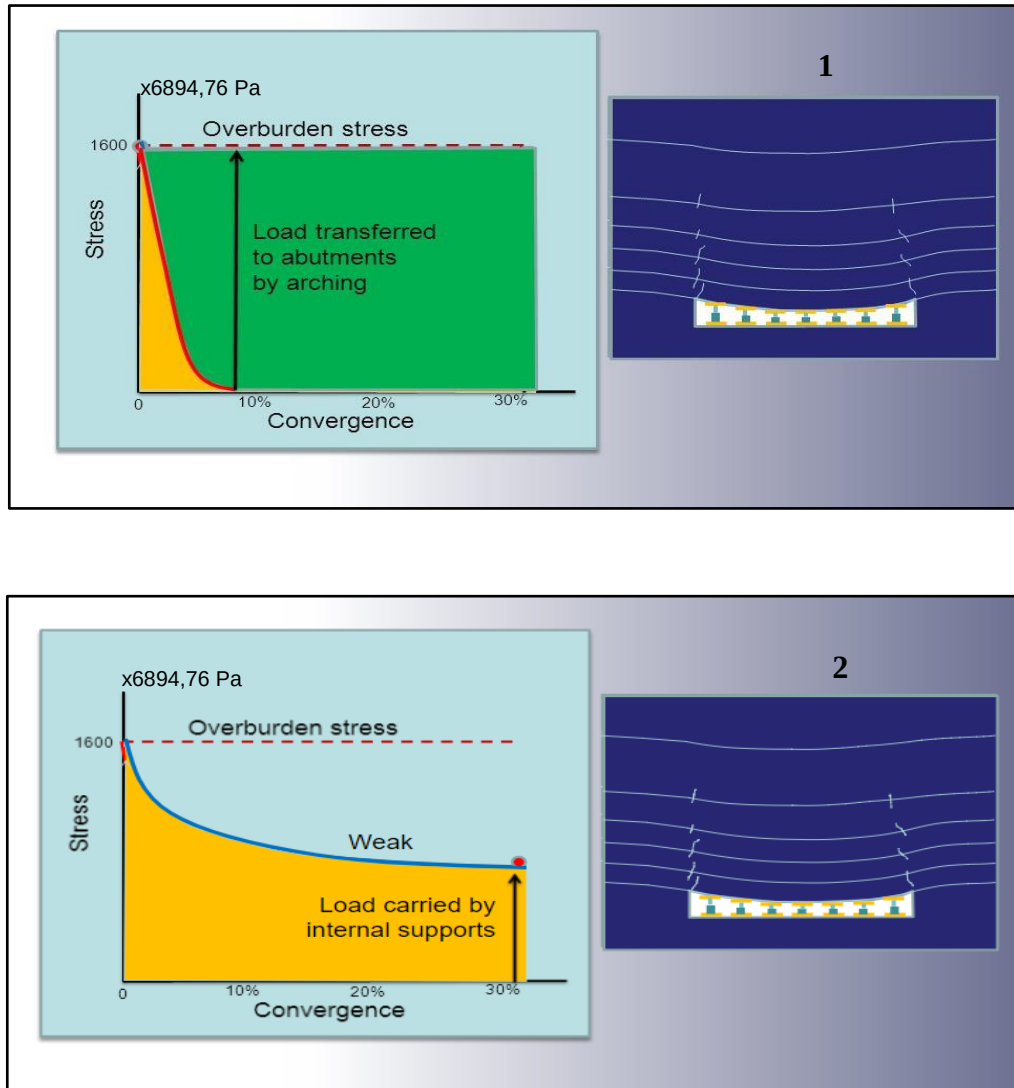


Figure 2.4-2- Overburden behaviour as a result of its stiffness represented by ground response curves, where (1) shows stiff overburden and (2) shows weak/soft overburden (Esterhuizen, et al., 2006)

For the same value of overburden stress in Pa (Pascal), stiffer overburden (represented in image 1 of Figure 2.4-2) reduces the percentage of panel convergence. The rate of convergence is controlled as the overburden transmits its weight, either to the front abutment ahead of the coal face or behind the coal face (Kumar, 2015). Whilst a softer overburden (represented by image 2 of Figure 2.4-2) shows that a substantial proportion of the overburden load is carried by the internal support, by an increase in pillar strain inflicted by the overburden deflecting.

Surrounding strata properties: Bridging capability of overburden

For ultimate coal pillar failure to occur, not only do pillars have to be loaded beyond their load-bearing capacity but the overburden has to deflect at a certain amount to completely deform the pillars (Mining weekly, 1996). This introduces the self-supporting capacity of the overburden such that panel collapses (caused by in-panel pillar failure) can be prevented by minimising panel widths. By allowing the overburden to self-support, it reduces the load transferred by deflection of the overburden.

Figure 2.4-3 demonstrates the effect of panel width on the load imposed within a panel. Wider panels experience larger values of overburden stress for the same amount of convergence experienced in narrower widths. Van der Merwe, found a link between overburden deflection and pillar load that causes pillar compression, implying that a pillar cannot compress by a quantity greater than the overburden deflection and vice versa (Mining weekly, 1996).

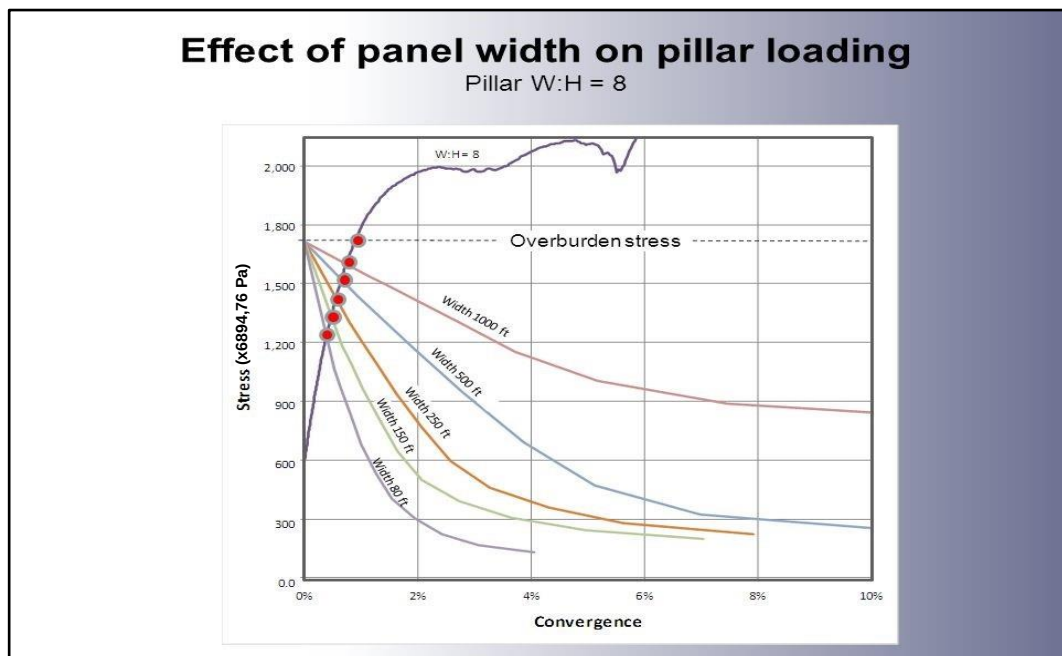


Figure 2.4-3 -The effect of panel width on pillar loading (consisting of pillars within a panel with a w/h ratio of 8) (Esterhuizen, et al., 2010)

Interface between immediate roof and floor on the coal seam

The extent of the stress pattern and deformation within a pillar is controlled by the contact interface between the coal seam and the surrounding rockmass (Iannacchione, 1990). The nature of the interface is driven by two material properties: cohesion and the angle of internal friction, which is generally less than the value of coal (York, et al., 2000). Similar to discontinuities, these interfaces act as boundaries for potential failure. Slip between the interface and the coal seam develop, caused by the stress concentration within pillars induced by mining, as the frictional resistance reduces. Furthermore, slip failure deteriorates the horizontal stress component along the interface reducing pillar confinement, perpetuating slip failure as the vertical stress increases into the pillar core (Iannacchione, 1990).

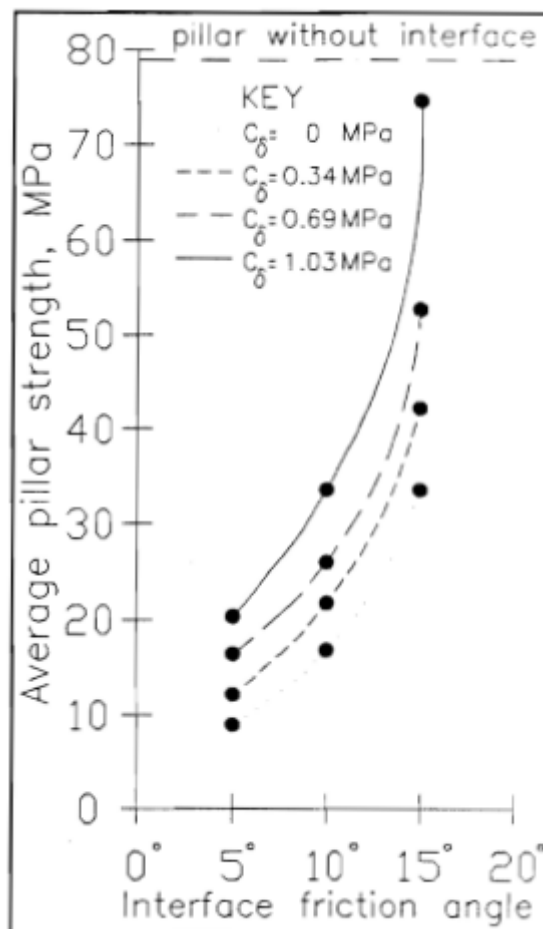


Figure 2.4-4- Interface of different properties for vertical stress gradients for the same loading environment (Iannacchione, 1990)

The influence of the interface slip mechanism on pillar behaviour is best illustrated by observing stress profiles during loading and by measuring the ultimate strength, as demonstrated in Figure 2.4-4. The figure indicates that the interface slip mechanism tends to control the rate at which the inelastic yield zone (periphery of pillar) develops in response to increasing increments of applied pressure (Iannacchione, 1990). The inelastic zone describes the area of a pillar where permanent deformation occurs (Wilson, 1972). The implication is that the pillar load increases with a poor contact interface. Different shaped vertical stress profiles are created based solely upon the interface material properties, which in turn alter the load-bearing capacity of a pillar.

Presence of discontinuities

Discontinuities have the ability to concentrate or reduce the stress field within a pillar, depending on its proximity to excavations and depth (Stacey & Wesseloo, 2002). As previously discussed, stiffer materials tend to attract stress, so the stress concentration in say a dyke may be higher than in a rock such as sandstone that would be in close proximity. The effects of this may cause some change in the magnitude and distribution of the vertical stress, affecting a pillars load-bearing capacity and likely to perpetuate early failure.

The loading of pillars with time

Ultimate strength formulations assume that the load across the volume of the pillar is distributed uniformly, which realistically is inaccurate. As illustrated in Figure 2.4-5, load transfer is concentrated nearer to the pillar ribside, particularly in the corners, increasing with time (Galvin, 2016). As the edges of the pillars are least confined, they yield at lower load values (York, et al., 2000). This can further be enhanced by roof sag that induces load nearer to pillar sides. With time, strain gradually increases as the load remains constant. In the case where the size of the pillar is not sufficiently large, failure may occur under the time-dependent strain although initially showing signs of stability.

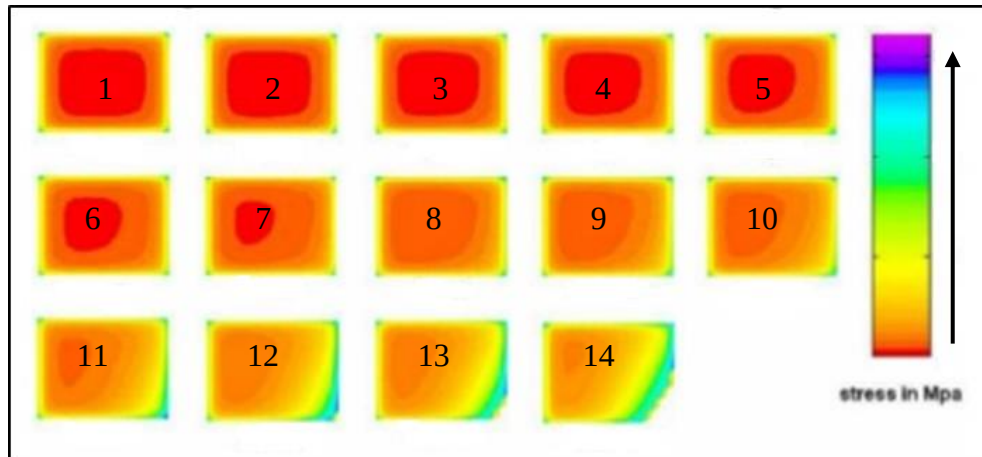


Figure 2.4-5- Plan view showing the stages of pillar loading with time (Sankar, 2011)

Wilson (1972), suggested that pillar boundaries are likened to an inelastic yield zone, whereas the core behaves as an elastic zone. Its significance is that the inelastic yield zone, permanently deforms in the form of scaling or fracturing along the pillar ribside, whilst the pillar core would remain intact.

Kumar (2015), describes three stages of pillar loading during and post-coal extraction:

- Preliminary loading - This type of loading occurs immediately after an excavation has been developed;
- Subsequent loading or abutment pressures - Transmission of overburden stress to the front and back abutment, relative to the coal face;
- Post-mining loading - The progressive failure of pillars, is best described by the strain-softening mechanism of rockmasses. With progressive overburden loading with time, the pillars resistance to deformation deteriorates (Galvin, 2016). At yield strength, the pillar fails unable to carry its load maintaining a residual strength.

Seismic effect on loading caused by blasting

Drill and blast was previously used to mine at the No. 2 Seam prior to mechanised mining which was introduced in the late 20th century. Vibrations caused by blasting, using the drill and blast method could have caused dynamic loading of pillars, particularly where dykes may have been intersected. Given that a rockmass is anisotropic and consists of joints, the blocks formed by joints that intersect in a rockmass loosen up and fracture due to a reduction in the frictional resistance along the joints (Stacey, 2017).

Multiple seam mining

It is quite common for a leased area to contain seams overlying one another, especially within the Witbank coalfield. The position of the seam relative to each other affects the percentage of recovery from each seam, simply by their interaction (Van der Merwe & Madden, 2010). A set of rock engineering guidelines or design procedures were developed by Salamon and Oravecz (1976) to resolve the effects of seam interaction on pillar loads, more so pillar stability. The rock engineering guidelines are based on the thickness of partings between the seams in relation to the centre distance and the bord width within a layout.

Salamon and Oravecz (1976) and Bradbury and Lear (1984) established that at a vertical distance greater than 0.75 to 1 times the centre to centre distance, the alternating stress influence of bords and pillars becomes less. The stress value at this limiting distance above mine workings returns to the virgin stress state, caused by a decrease in mining depth and an increase in pillar size. The distance at which the stress transfer occurs is a function of the nature of the rock, particularly the rockmass stiffness.

Stiffer material or material with a higher elastic modulus i.e. sandstone, can withstand higher stress without deforming, thus decreasing the transfer distance of loads whereas less stiff materials i.e. shales, increase the transfer distance, deforming substantially (Ehgartner, 1982). Additionally, the shape of pillars within a layout affects the stress transfer over a distance. Chekan and Matetic (1988)

reported that the interactive distance is controlled by the least width of the pillar, proven by the effective width equation ($W_e = 4A/2P$; where A is the area of the quadrilateral and P is the perimeter in meters). Therefore, rectangular pillars shed less of their load over a shorter distance than square pillars of an equal load-bearing capacity.

In the case where mine workings were developed prior to the compilation of multiple seam rock engineering guidelines by Salamon and Oravecz (1976), seams would have been mined with little knowledge on how the layout would affect the extraction and rockmass behaviour of an under/overlying seam. It is possible that damage to the areas mined caused by flooding, subsidence and spalling of pillars would have occurred with time but would not be known as these mined areas are generally inaccessible (due to lack of roof support or flooding). The long-time effect of these conditions on the next seam is difficult to anticipate and pose a problem when secondary extraction (e.g. coaling) is considered.

2.4.3 Potential methods to estimate coal pillars loads

Currently, six potential methods are commonly used to estimate the coal pillar load: tributary area theory (TAT), analytical method, beam deflection theory, photo-elastic analyses, pressure arch theory and numerical modelling (Roberts, et al., 2002). Of the six methods, two are briefly investigated in Appendix A, being the tributary area theory (TAT) and pressure arch theory (PAT) due to their simplicity in providing a pillar load estimate and accessibility.

The choice of which technique/s would be most suitable depending on these main factors:

- A method that can estimate the overall stress environment within a complex (irregular) layout, post-mining;
- A method that can account for the influence of the rate of extraction on pillar load, since pillar height is expected to change by coaling;

- A method that can show the change in stress trajectories, including the stresses in the lateral direction;
- A method that is not time-consuming or expensive and that can provide a relatively quick estimate of the average pillar load;
- A method that accounts for all, if not most controlling site-specific parameters to estimate pillar loads.

Of the two methods, the pressure arch theory would be suitable for two-dimensional stress-analysis considering the time constraint of the research and applicability to irregular bord and pillar layouts. In addition, to prove to an extent that the pillars remain stable (within their functional objective) despite TAT's over compensation of stress values, a 2-dimensional analysis is feasible. However, the most feasible would be numerical analysis as it is a great way to understand the possible behaviour of the interaction of the rockmass and pillar, giving a range of variability of the outcomes.

2.4.4 Influence of mining on stress magnitudes with a change in mining height

Due to the nature of the bord and pillar mining environment, displacements in the near stress-fields are restrained as a way to prevent subsidence of the overburden. As soon as a pillar is formed in a coal seam, mining-induced stresses develop a pressure arch over it, initially remaining confined over the edge of the pillar (Singh, et al., 2011). By the restriction of displacements, the stresses inflicted on the pillars enlarge with time. The near-field stress behaviour is controlled mainly by the pillar design, whereas panel secondary zones (i.e. roof or pillar ribs) achieves stability through various forms of artificial support such as roof bolts (Brady & Brown, 2006).

Majumder and Chakrabarty (1991) found that the mining-induced stress increases proportionally with decreasing seam thickness. This increase in the maximum stress was caused by the reduction in seam thickness, which generates a higher strain in

the coal adjacent to the roadway. In turn, it produces higher loads on the pillar edges (edge of roadway). With the progressive growth in pillar stress magnitudes, pillars degrade quicker.

2.5 Pillar strength estimation

2.5.1 Introduction

Following the 1960's Coalbrook disaster, rock mechanics research into pillar behaviour, particularly pillar strength, became crucial for the preservation of the South African coal industry. Numerous investigations have contributed to the study of the strength of coal pillars, which led to the development of empirical and analytical formulae. Although the equations have demonstrated their reliability in providing safer working environments, over the past two decades, coal research has been quite stagnant (Mathey & Van der Merwe, 2016). As a result, an extensive critique of the applicability of the current strength formulations used in South Africa is required where the limitations of the equations' conception often reduce optimal extraction (Van der Merwe, 2016a).

Furthermore, in light of the increased use of renewable energy resources within Organisation for Economic Co-operation and Development countries, the popularity of using non-renewable resources, e.g. coal has been cut down within the export countries, compelling the coal industry to improve their mining method (Energy Information Administration, 2013).

Similar to pillar load evaluation in the previous section, this section will review the factors that affect pillar strength, which is subject to change upon coaling. This is followed by a critical analysis of the current strength formulas used specifically at the No. 2 seam. Additionally, numerical analysis of pillar strength and ground response curves are analysed, given its current use and popularity within the industry.

2.5.2 Influencing factors on pillar strength

Like pillar load estimation, varying factors control the magnitude of a pillar's compressive strength which include (Maritz, 2015) :

- Rock material characteristics
- Deposit characteristics
- Loading conditions
- Pillar size and shape
- Discontinuities such as joints, faults, bedding planes and waste bands

With a wide range of literature available providing extensive details on their effect on a pillars strength, the only factors considered within this section would be those that are subject to change upon bottom/top coaling; being the pillar size and shape. Other factors also include the loading environment which has been briefly reviewed in Section 2.4.

Pillar size and shape

The strength of coal pillars is a function of its size and shape. The size effect portrays the decrease in average strength of a pillar, with an increase in the volumetric size of specimens tested (Bieniawski, 1967), as shown in Figure 2.5-1, whilst the shape effect portrays the effect of a pillars' geometry and volume on its strength (Van der Merwe, 2001). Both the effects are demonstrated by in-situ and laboratory tests reviewed by various authors.

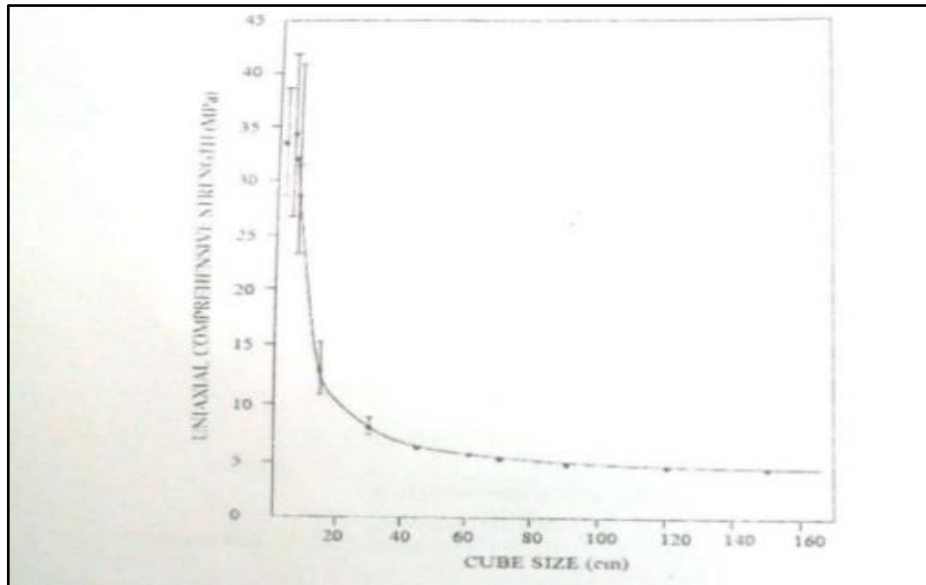


Figure 2.5-1- Graph showing the relationship between the size and strength of a specimen (Bieniawski, 1967)

For the purpose of the investigation, it would be worthwhile to take note of the shape effect since pillar height is proposed to change upon coaling.

Size effect

Bieniawski (1967) demonstrated the effect of specimen size on the compressive strength of coal, by indicating the relationship between the load at failure and cross-sectional area of a pillar (Tsur-Lavie & Denekamp, 1981). The research took place underground within the Witbank No. 2 Seam, such that pillars of varying sizes (up to 2m) were tested, applying an axial load perpendicular to the coal bedding. The in-situ test demonstrated that coal strength decreases with increasing specimen size, due to the presence of discontinuities with an increase in sample volume size, as illustrated in Figure 2.5-2.

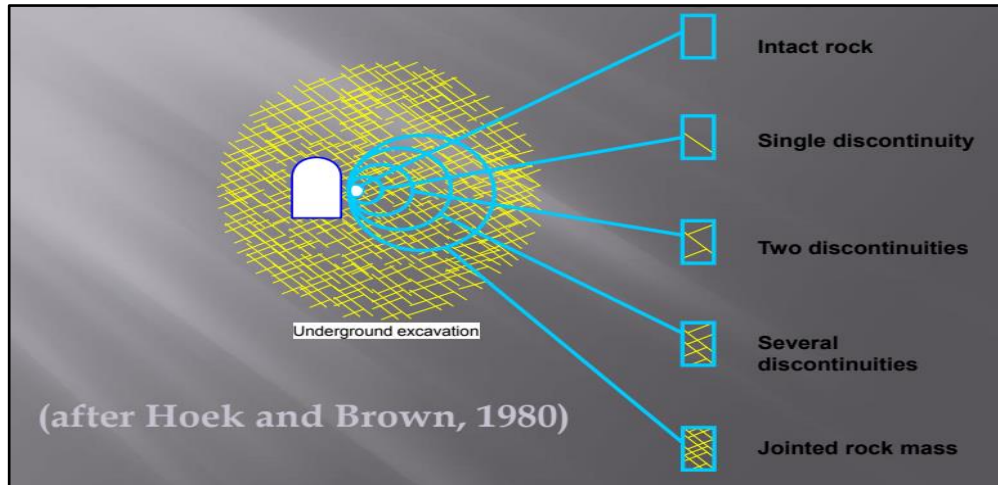


Figure 2.5-2- The transition from intact rock to heavily jointed rockmass with increasing sample size (Hoek & Brown, 1980)

However, from Bieniawski's (1967) research, it was apparent that smaller samples (without the presence of discontinuities) provided a realistic interpretation of the coal strength of true sized pillars (Tsur-Lavie & Denekamp, 1981). With the presence of discontinuities, the in-situ sample strength decreases by 10-50%, as compared to samples tested in laboratory environments (Poulsen & Adhikary, 2013). At a size of 1,5m, Bieniawski (1967), found that the strength of coal reaches an asymptotic value. At any size above this critical height/size, the strength of coal is believed to remain the same, even if it were to lengthen.

Poulsen and Adhikary (2013) also interestingly found that the mass strength of coal is quite uniform between coal producing basins, such as South Africa and Australia, where the coal strength values only vary by 1,5 MPa, ranging between 5,4 MPa to 7,4 MPa. This may allow the use of strength equations formulated from the Australian coal environment within South African coal mines for similar geotechnical conditions.

One of the setbacks of Bieniawski's in-situ test was the application of the load in one direction, that being uniaxially or vertically. Since a rockmass is anisotropic; meaning that it consists of mineral grains, cracks and pores at random orientations, it would be suitable to apply loads at different orientations to estimate the true

behaviour of coal samples, particularly at larger sizes. Van Heerden (1975) simulated underground conditions of coal specimens (applying loads at different directions for e.g. in the horizontal direction) within a laboratory. The outcome of the experiment showed that the site-specific strength of coal is about three times higher with increasing specimen size (assuming no discontinuities are present) than that predicted by the back-analysis of collapsed cases.

Shape effect

The shape effect essentially entails, that less stiff pillars exhibit a strain-softening behaviour when its dimensions are less than the critical width to height ratio of 5, which may only be true if no foundation failure occurs from FLAC modelling (Hopkins, 1993). Less stiff pillars yield at a peak load, whilst stiffer pillars exhibit a strain-hardening behaviour, increasing exponentially in strength, as the load increases, as depicted in Figure 2.5-3 (Sankar, 2011). Slender pillars are therefore prone to deform quicker for a given load and are more likely to fail by their brittle behaviour (Tsur-Lavie & Denekamp, 1981).

Hence, with an increase in height both the w/h ratio and pillar strength decreases and vice versa for pillar width. Mathey and Van der Merwe (2016) argued against the exponential increase in pillar strength caused by a w/h ratio greater than 5. The authors agree that the exponential increase in pillar strength is caused by the transition from brittle failure to quasi-ductile failure.

Therefore pillars higher than the critical width to height ratio tend to maintain their load-bearing capacity even with the loss of cohesion, caused by spalling, as illustrated in Figure 2.5-4. The change in the failure mode, occurs as the development of single continuous fractures is limited to the boundary of the pillar, keeping the pillar core intact and thus a higher value of strength is expected for squat pillars (Tsur-Lavie & Denekamp, 1981).

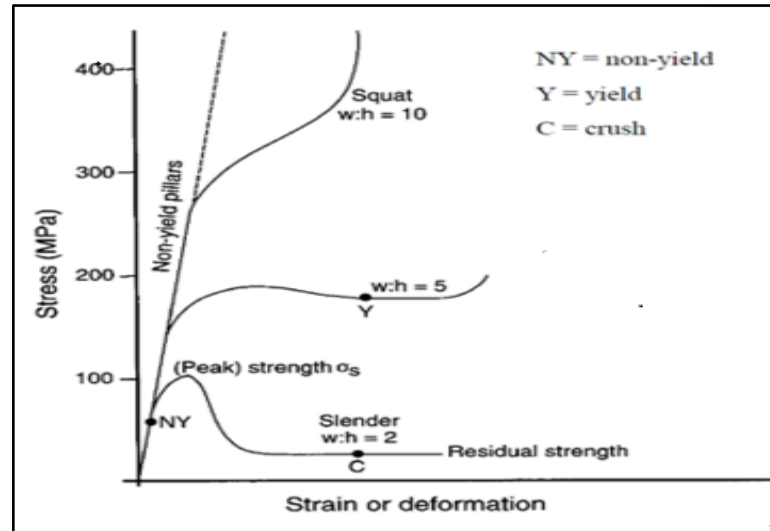


Figure 2.5-3- Stress versus strain relationship of pillars differing in width to height ratios (Sankar, 2011)

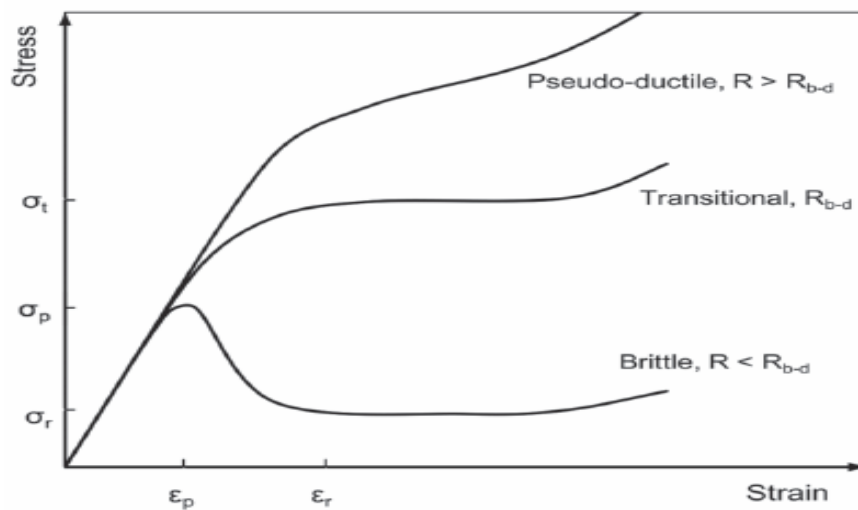


Figure 2.5-4-Stress versus strain graph showing the transition from brittle failure to quasi-ductile behaviour with increasing width to height ratio of pillars (Van der Merwe & Mathey, 2016)

2.5.3 Empirical strength formulae

Coal pillars are designed according to their functional requirements within a mining layout, which is in accordance with the empirical formulae chosen, particularly the strength equations (Jeremic, 1985). Various pillar strength equations have been derived using laboratory compression tests, large in-situ compression tests, case

studies of collapsed and stable pillars (including those that are site specific), closed-form methods and mixed methods. A desirable equation for economical extraction of a seam deposit would be one that meets the following requirements (Sheorey, 1993):

- I. The equation should fit as many collapsed and stable cases as possible;
- II. It should be applicable to both slender and squat equations;
- III. Incorporate as many factors that influence pillar strength.

Generally, the equations derived in South Africa were developed for slender pillars, with Madden (1988) developing the squat equation with the assumption of the increase in mining depth in South Africa, which is more applicable to the Waterberg and Kwa-Zulu Natal coal seams. Most case studies within South Africa were developed where mining width to height ratios rarely exceeded 4, the depth remained relatively at 250m and mining height maintained at 3m, particularly in the Witbank area, which warranted equations specific to slender pillars (Mathey & Van der Merwe, 2016).

Coal pillar strength equations specific to the South African coal environment

The development of coal research has received extensive critique on the derived strength equations, allowing for updated versions and the introduction of new equations from the statistical characteristics of collapsed cases. Part of the reason of the critique is the lack of verification of the applicability of the equations to all seam specific environments and inadequate prediction of pillar behaviour (Van der Merwe & Mathey, 2013a).

The trend of most empirical formulae is they merely predict the average strength of a specific group of coal pillars, explicit to those that have collapsed and excluding those that remain stable. Although the empirical formulae are quite useful as design guidelines to prevent further collapses, they do not necessarily predict the actual

strength of any given coal pillar. Mathey and Van der Merwe (2016) concur that there is sufficient evidence to assume that the actual strength of coal pillars may be highly variable. Differences in pillar strength between coalfields (Van der Merwe and Mathey, 2013b) and groups of seams (Salamon, et al., 2006), have been proposed by the mentioned authors.

Some of the issues of empirical formulae are given as (Van der Merwe, 2001):

- Confidence in and completeness of databases
- Role of geology
- Adequacy of load estimates
- The link between the factor of safety and failure probability
- Linear vs power formulae
- Accounting for pillar volume
- Non-square pillars
- Influence of coal material strength
- Extrapolation beyond limits of the database
- Data collection protocols
- The statistical rigour of analyses

These issues must be considered when choosing an equation that is the best fit for a seam deposit. Often collieries tend to use more than one equation to establish the variance in pillar strength. Furthermore, it is important to take note of the relative strength of the pillar interfaces such as floor and roof when coaling takes place with respect to the use of failed and intact pillar cases empirical formulae, particularly for this project. As illustrated in Figure 1.2-1, if bottom coaling is done a ‘competent’ sandstone floor would be achieved which is within the limitations of all empirical strength formulae specific to the Witbank coalfield. However, if top coaling is done, the roof would be a weaker shale, and thus the empirical formulae may not necessarily apply given the limitations in Table 2.5-1.

To date, five equations are used within the Witbank coal area: Salamon and Munro formula [old and updated] (1967; 1996), Bieniawski strength formula (1992), Squat pillar formula (1988), Van der Merwe pillar strength formula [old and updated] (2003,2013b) and Seam 1, 2, 4 specific strength equation (Salamon, et al., 2006). The methodology, application and limitations of the formulae are described in Table 2.5-1. From the summary, two methodologies were used during the development of the formulae: back analysis (case studies of failed and intact pillar cases) and large in-situ tests. The majority of the strength equations formulated were developed from case studies of failed and intact coal pillars in South Africa.

Table 2.5-1-Summary of pillar strength equations used in the Witbank coalfield

Author	Equation	Methodology	Application	Limitations
1. Salamon, et al. updated formula (1996) 2. Original Salamon formula (1967)	$\sigma_s = 6, 88 \text{ MPa. } w^{0,5}/h^{0,7}$ (maximum likelihood) $\sigma_s = 7, 18 \text{ MPa. } w^{0,46}/h^{0,66}$ Where: w- Pillar effective width (m) h- Pillars height (m)	Case studies (Aus., S.A)	- Slender pillars ($2 \leq w/h \leq 5$) - The diameter of the failed area is greater than mining depth - FOS between 1,3-1,9 - The panel must be at least as wide as the depth of mining - Pillars must be equally	Tributary area theory is applied Pillars are assumed to be square Floor conditions of the area must be competent, not affecting the type of pillar failure Ignores the effect of surrounding roof and floor on coal pillar strength Ignores friction in the interface of coal seam on coal pillar bearing capacity Pillar failures due to the mining of two or more seams were excluded from the database Excluded 21 cases where the weak roof or coal deterioration occurs

			spaced and shaped	Underestimates pillar strength
3. Bieniawski (1992)	$\sigma_s = 4,3 \text{ MPa} (0,64 + 0,36 \cdot w/h)$ Where: w- Pillar effective width (m) h- Pillars height (m)	In-situ tests of large coal specimens underground (Witbank area, Largo mine)	- Slender pillars $(2 \leq w/h \leq 3,4)$ - Squat pillars $(5 \geq w/h \geq 12)$ - Can be used in room and pillar, as well	Assumes that geometrically similar pillars have the same strength Shape and size of pillar have the most influence on strength Ignores influence of fractures, cleats and partings on pillar strength Included only 27 failed pillars in statistical analysis Tests was performed in one area Predicts lower pillar strength for all width to height ratios

			as longwall mining • FOS range between 1.5-2.0 • Consists of a generic formula that can be applied to any coal seam of a specific strength	
4. Salamon, Canbulat and Ryder (2006)	$\sigma_s = 6,187 \text{ MPa} \cdot w^{0,67}/h^{0,87}$ Where: w- Pillar effective width (m)	Case studies (S.A) (Divided into different geological areas)	• Only used at No 1,2 and 4 Seam at Witbank Coalfield • Slender pillars	Suitable for pillar extraction and the design of chain pillars along longwall panels Ignores time-dependent scaling with the associated weakening of pillar and increase of load

	h- Pillars height (m)	specific to the coal seam)	$(2 \leq w/h \leq 4,1)$ FOS of at least 1,63 to ensure stability	
5. Van der Merwe (2013b),(2003)	$\sigma_s = 5, 47 \text{ MPa. } w^{0.8}/h$ (overlap method) $\sigma_s = 3, 5 \text{ MPa. } w/h$ Where:w- Pillar effective width (m) h- Pillars height (m)	Case studies (S.A)	- Slender pillars $(2 \leq w/h \leq 5)$ - FOS of at least 1,3 for stability	Newly developed, so may lack credibility since it is new. However, is currently used in some coal mines.

6. Madden (1988)	$\sigma_s = 7, 2 \text{ MPa. } (R_0^{0,5933} / V^{0,0667})$ $\left\{ \frac{0,5933}{\epsilon} \left[\left(\frac{R}{R_0} \right)^\epsilon - 1 \right] + 1 \right\}$ Where: R_0 is the critical width-to-height ratio R is the width-to-height ratio of the squat pillar V the pillar volume ϵ a parameter which controls the rate of strength increase with increasing R in squat pillars	Case studies (S.A) Laboratory test	- Squat pillar $w > 5$ - Can be applied to different geological and structural environments	Predicts that pillar strength exponentially increase when the width-to-height ratio is greater than five (incorrect) when it is caused by the change in the failure mode of pillars. (Squat effect is believed to occur when w/h ratio is greater than ten) The absence of squat pillar collapses, assumes failure will not occur (Squat pillars are overdesigned thus assumed to not fail)
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Alternative methods for coal pillar strength estimation

Provided that failed and intact pillar cases exist within the region of investigation, it is possible to estimate the strength of coal pillars using ground response curves and numerical modelling to better understand coal behaviour. In both methods, the behaviour of the pillar as it transitions from elastic to plastic zones is considered. This provides a means to evaluate its performance capability particularly since coal is characterised by its strain-softening behaviour (Fahrman, 2016).

Ground response curves (GRC) to estimate pillar strength

The GRC estimates the behaviour of a rockmass surrounding an excavation based on the applied pressure of a support system and the resultant convergence of the excavation (Esterhuizen, et al., 2010). This establishes the relationship between the deformation characteristics of a support system (coal pillars) and the overburden by their stiffness (Galvin, 2016).

The line PQR, in Figure 2.5-5, represents the stress-convergence response of a support system consisting of pillars. The curve illustrates the resistance required by a pillar. On the vertical axis, the support pressure/stress required by a coal pillar represents the pillar strength and convergence is described by a pillars' strain. From extraction of the coal within the seam, the overburden compresses the pillars increasing in convergence. Therefore the support pressure required by the pillar can be indicated at the point of intersection, between the rockmass ground response curve and support response to convergence.

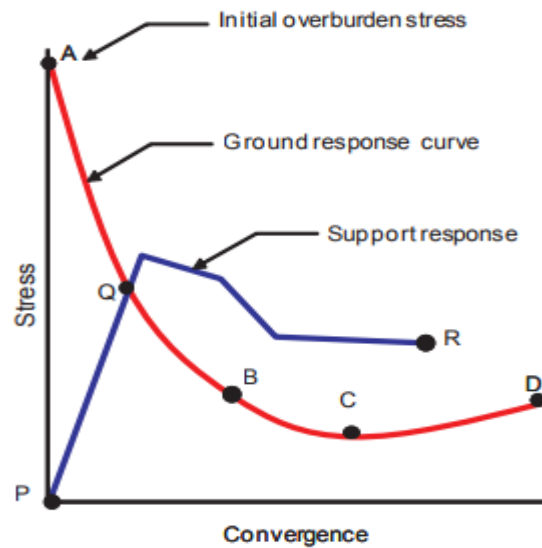


Figure 2.5-5- Ground response curve of support to estimate rockmass behaviour (Esterhuizen, et al., 2010)

Ground response curves do not consider the fact that a portion of the overburden weight may be transferred to adjacent unmined barrier pillars or solid abutment, as a result of a pillars spatial relationship within a layout when the Tributary Area Theory (TAT) is used to determine pillar loading (Fahrman, 2016). The difficulty arises during the measurement of the ground response curve within actual underground excavations, as a great portion of the loads would have to be applied to balance the original ground pressure (Esterhuizen, et al., 2010). By using numerical models, the use of ground response curve's accuracy improves by progressively reducing the internal pressure in a modelled excavation whilst monitoring the resultant convergence.

Numerical modelling methods to estimate pillar strength

By calibrating the numerical model of failed and intact pillar cases, the strain-softening behaviour of coal is estimated by estimating a residual strength to establish coals peak strength. The back analysis of the data provides the constitutive parameters of the coal mass. During the process, the material behaviour is likened to the Hoek-Brown strain softening material, given that the original Hoek-Brown failure criterion applies specifically to isotropic rockmasses (Hoek & Brown, 1980).

Additionally, the value of m_i that describes the intact rock specimens tested normal to bedding or foliation would be significantly different if failure occurs along a weakness plane such as a joint. Using this technique, pillar design is not only based on pillar strength but also considers the post-failure behaviour of an array of pillars (Fahrman, 2016).

2.6 Stability criteria

2.6.1 Introduction

As deterministic methods only account for the inherent variability of the rockmass in the FOS, using non-traditional stability analysis allows evaluation of support design by its reliability to remain stable. The assessment of stability would then be achieved through an analysis of the statistical distribution of parametric variability rather than a mean value of FOS (Griffiths, et al., 2002).

The goal of stability forecasting is to identify the state at which under variable loading conditions, would an excavation experience increasing, indefinite deformation (Beck, 2008). In addition, forecasting intends to estimate the time when the failure of the excavations would occur. This aims to prevent catastrophic failure of pillars within an excavation. Thus, instability is defined by a condition of loads and velocity which can differ from failure to failure (Beck, 2008).

This section looks at the stability limits required for coaling to take place and the stability criteria other than the factor of safety to estimate stability in a coal pillar support system that will be subject to secondary extraction. The criteria include the probability of failure (POF), the probability of survival (POS), the rate of scaling, a factor of stability and width to height ratio.

2.6.2 Suggested stability limits for coaling

Galvin (2016) provides the stability limits in terms of a value of FOS for safe and economic coaling. The stability limits were developed in the United States and

therefore should be used as a guideline as it is not specific to the South African coal environment. The limits are given as:

Top coaling

By rule of thumb, provided by Salamon and Munro, safety factors of primary workings should be 2.5. Upon final design, FOS in some countries can be 1.4 on condition that top coaling is done on retreat (in the opposite direction of mining) and bottom coaling is done in advance (in the direction of mining), shown in Figure 2.6-1.

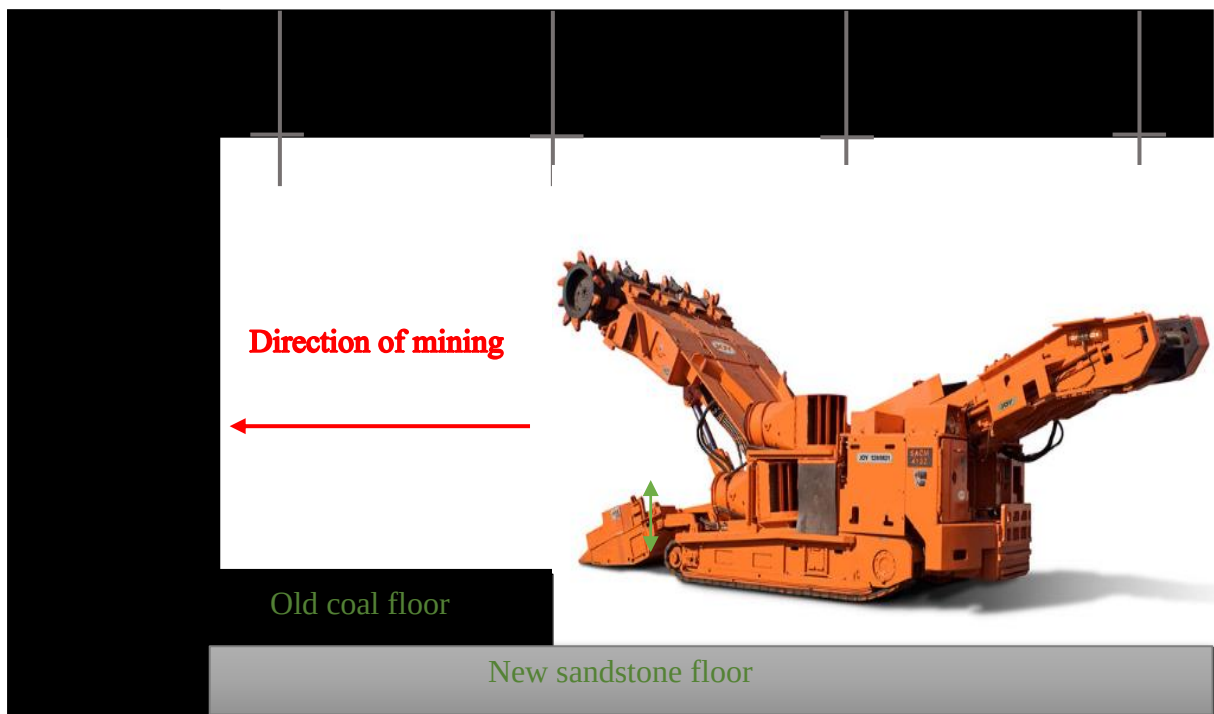


Figure 2.6-1- Bottom coaling at No.2 Seam in the direction of mining

Bottom coaling

Like top coaling, the worked areas must have a FOS value of 2.5 from primary development. Upon coaling, the value of FOS should not be less than 1.6 based on the final extraction height.

These stability limits will be used to determine the feasibility of coaling at the No. 2 Seam, using some of the criteria mentioned within this chapter.

2.6.3 Probabilistic or reliability of design for secondary extraction

Introduction

Theoretically, where true values of pillar strength and load are known it is assumed that SF values greater than 1 means the pillars are stable, whilst an SF value smaller than 1 implies instability and consequently failure. Hence in practice, an SF value higher than 1 (whereby in South African it resides at 1.6) is used as a design level to account for the geotechnical uncertainties, as neither the load nor the strength of pillars can truly be determined. The extent as to how much more stable a pillar system may be, by using a safety factor greater than 1 cannot be quantified.

Prediction of the stability of support requires a certain level of confidence from the deliberation of risk associated with the reliability of a support system (Stacey, 2017). By evaluating the reliability of a system using the POF, ambiguity is removed which is caused by using different strength formulae to estimate stability. For the same FOS value, larger pillars were derived from strength formulae, using Salamon, et al. (1996) maximum likelihood method, whereas smaller pillars were calculated using Van der Merwe's and Mathey's (2013a) overlap method. The results were that larger pillars had a lower POF than that for the smaller pillars. By using the same pillar size, Van der Merwe and Mathey (2016) discovered that the POF derived for the two different formulae (maximum likelihood method by Salamon and overlap method by Van der Merwe) were more or less similar.

Salamon, et al. (1996) first brought to light the statistical link between the safety factor and the POF of coal pillars by utilizing the updated cumulative frequency distribution of failed safety factors only. The shortcoming of the work of Salamon, et al. (1996) was made clear, as it only considers the frequency distribution of safety factors of failed pillars, but ignores frequency of intact pillars FOS (Van der

Merwe & Mathey, 2013b). For all probabilistic methods mentioned, the FOS is used as an input to the developed equations.

Estimating the pillars' POF, POS and rate of scaling

A three-tier method was developed by Van der Merwe (2016) to estimate the stability of current coal pillars in the Witbank and Highveld coalfield. The method aimed at quantifying the probability of survival (POS) as a function of time, and the rate of scaling of pillars. By evaluating 337 cases of mine plans, it extended the initial 98 cases used by Salamon (1967). This was done by interpolating pillar sizes creating a new data set for evaluation since quantifying the pillar sizes, at the different mines was not feasible due to inaccessibility.

Three equations were used to estimate stability within the areas: Probability of failure, the probability of survival and rate of scaling with the intent of estimating the life of pillars. As mentioned previously the probabilistic values are determined using the value of FOS, from equations specific to the two coalfields. However, for the study, the values were estimated based off Figure 2.6-2 and Table 2.6-1, as to allow the use of more than the two strength equations used by Van der Merwe (2016).

Estimating the Probability of Failure

The POF can be found from Figure 2.6-2 depending on the value of FOS calculated from the chosen strength equations. It is clear from Figure 2.6-2, that at a FOS of 1, the POF for a pillar or a panel would be 50% and at a FOS of 1.6, which is the standard used at coal mines, the POF of failure is given as 0,15%.

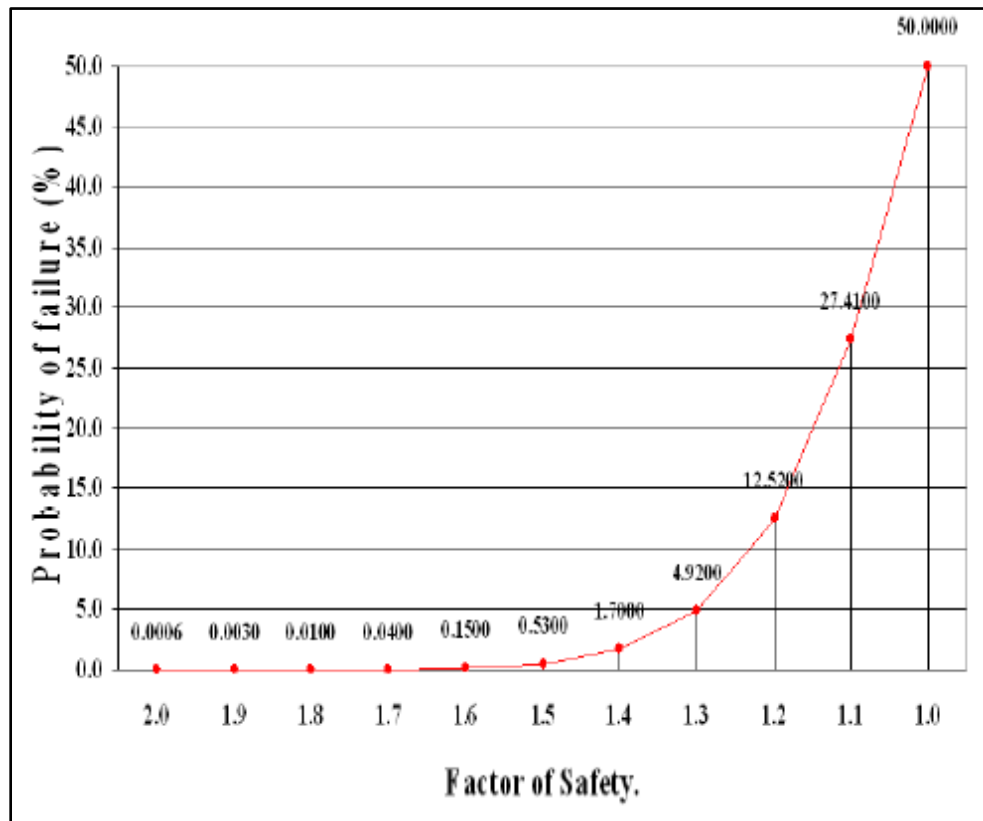


Figure 2.6-2- Probability of failure versus factor of safety (Brady & Brown, 2006)

Estimating the Probability of Survival

Depending on the excavation created, a percentage limit value known as the POS is provided to ensure that the excavation remains protected and stable as per its design requirements and to estimate a certainty of survival. This limit value is determined by subtracting a unit from a value of POF calculated for that specific excavation/s, shown by the Equation; $1 - \text{POF} = \text{POS}$. Table 2.6-1 provides a summary of the limits required for each of the respective excavation created in a mine. For the study, a production panel will be assessed in terms of its stability, hence the minimum required POS is given as 99%, in instances where structures occur 99,99% may be used.

Table 2.6-1-Proposed limits of the probability of survival for different categories of protection (Van der Merwe, 2016a)

Proposed limits of probability of survival (POS) for different categories of protection		
Category	Minimum POS (%)	Remarks
Production panel	99.0	Short term, limited access, low traffic
Secondary development	99.5	Medium term, general access, medium traffic
Main development	99.9	Long term, general access, high traffic
Surface structure (1)	99.99	Low sensitivity to subsidence
Surface structure (2)	99.995	High sensitivity to subsidence, public access

The rate of scaling:

Pillar scaling reduces the load-bearing capacity of a pillar and invariably its strength, as it expands into a pillar's yield zone (Wilson, 1972). The volume of material that has scaled surrounds the pillars and adds a confining effect depending on the height of the volume of the material relative to the height of the pillar along its periphery (Salamon & Oravecz, 1976). As a result, the rate of scaling may reduce caused by the confining effect affecting the post-peak mechanical behaviour of rock. However, this does not prevent failure but may reduce the rate at which failure occurs by protecting the pillar ribsides from the environment, avoiding further weathering on the pillar (Yu, et al., 2017). Moreover, the coal is less likely to remain surrounding the pillar boundary indefinitely. As a result, time should be included as a factor in stability analysis.

Estimating the rate of scaling

The rate of scaling by direct measurement is inversely proportional to age and directly proportional to mining height (Van der Merwe, 2016b). As can be seen in Figure 2.6-3 and Figure 2.6-4, the rate of scaling linearly increases with an increase in height, whereas scaling decreases reaching an asymptotic curve at the age of 50. Again, this asymptotic curve would be assumed to be caused by the limitations of the database to pillars widths up to w/h of 3.

Two equations were used to describe the rate of scaling - one relates to the mining height (in metres)/time (in years) parameter and another to the lifespan of pillars as

can be seen in Figure 2.6-3 and Figure 2.6-4 , respectively. From either equation, Van der Merwe (2016), indicated the scaling rates exhibit the same characteristics from the database as determined by direct measurement, merely differing by their constants. With scaling rate, pillar dimensions and FOS being known at the time of scaling, it is possible to predict the time at which pillars can be expected to fail. However, the certainty to predict failure may not be accurate given that the scaled coal may surround a pillar, providing a confining effect and thus limiting scaling.

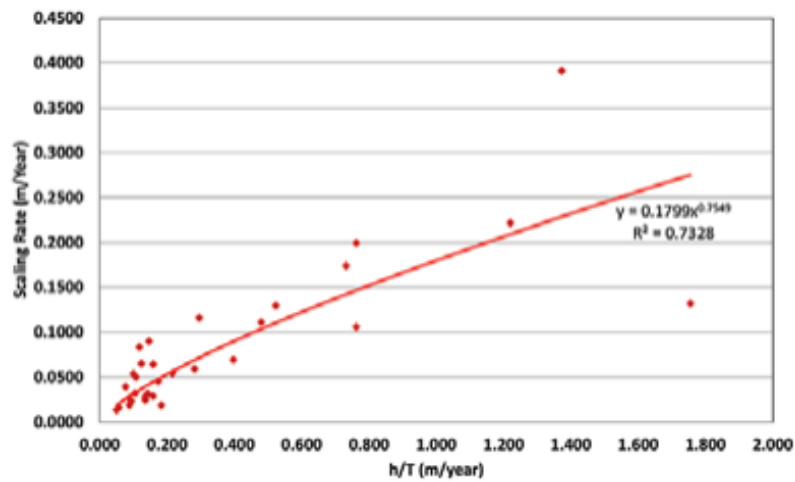


Figure 2.6-3- The rate of scaling versus h/t parameter (Van der Merwe, 2016b)

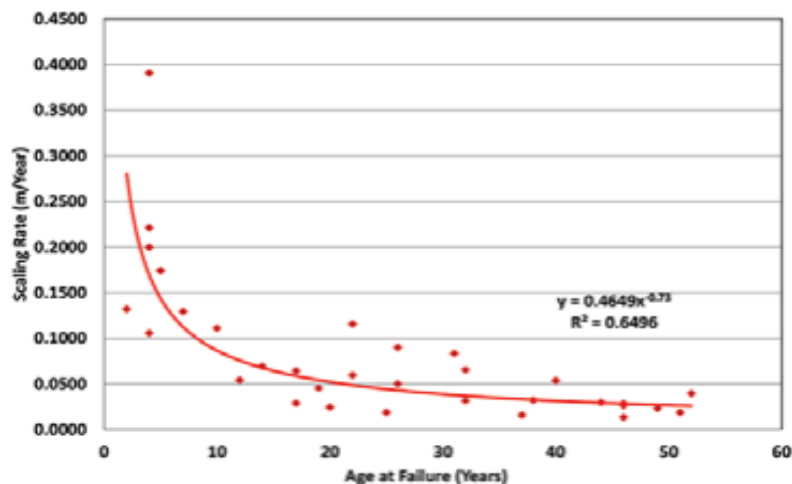


Figure 2.6-4- The rate of scaling versus the age of the coal pillar at failure (Van der Merwe, 2016b)

Due to the inaccessibility to old working areas, particularly in the Witbank coalfield, numerical modelling can be used to estimate the scaling rate of pillars, without using two different empirical methods, as provided by Van der Merwe (2016) to describe the rate of scaling. The modelling technique would also assume the behaviour of the pillars from back analysis of data as a means to obtain parametric data concerning the areas mined.

2.6.4 Factor of stability

Background

The influence of a pillar system and overburden stiffness greatly affects its load-bearing capability and more importantly, its post-failure behaviour when the pillars are stable. The post-failure behaviour of a support system contributes to its capability to maintain some form of deformation, allowing for a non-violent type of failure within a layout progressively with time (Guy, et al., 2017). The post-failure stiffness of pillars depends on the type of coal and their width-to-height ratio, showing an inversely proportional relationship (Pati, 2011). Post-failure stiffness has shown to become asymptotic at a w/h ratio above 2, as illustrated in Figure 2.6-5. At values below 2, post-failure stiffness tends to decrease rapidly.

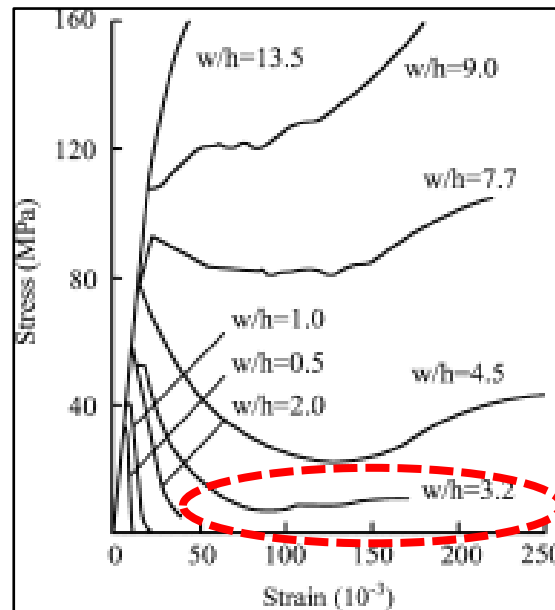


Figure 2.6-5- Graph showing the stress-strain behaviour of coal for a range of width to height ratio (Guy, et al., 2017)

By using the factor of stability through accounting for the relative magnitude of certain mechanical properties of the rock mass and of the pillar, possible pillar collapses can be prevented. The value of the factor of stability can be defined as the local mine stiffness versus post failure stiffness of pillars (Zipf, 2012). This describes the load-deformation characteristics of the coal roof and floor, whilst post failure stiffness describes stress conditions from laboratory tests to determine characteristics like magnitude of peak strength and the slope of the post-failure for different width and height ratio by using uniaxial testing (Sabapathy, et al., 2018). The values of the post failure pillar stiffness depend on the confining stresses and temperature conditions during the test. The post failure stiffness is illustrated as the tangent in Figure 2.6-6.

The initial development of the equation was based on the Salamon analogy of a rock specimen being loaded in a laboratory test frame aimed at determining whether the failure process of the rock specimen occurs in a stable, non-violent manner (Salamon, 1970). Throughout the derivation of the concept, the values used to

determine the conditions of stability was pre-existing empirical data of coal pillar failures within various mines in the United States of America.

Coal pillar failure mechanics

To technically justify the concept of the factor of stability regarding the mechanistic pillar design, it is crucial to consider coal pillar failure. Two critical elements are applied within a system: the post-failure stiffness of the structure (K_p) and the stiffness of the system that is directly loading the structure (K_M), illustrated in Figure 2.6-6.

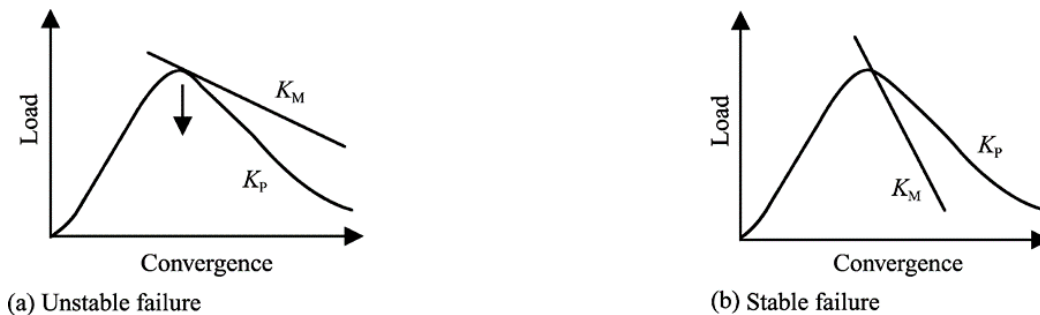


Figure 2.6-6-Unstable (‘soft’ loading system) (a) and (b) stable (‘stiff’ loading system) behaviour of a coal pillar system upon maximum loading (Guy, et al., 2017)

The concept describes the effect of the loading stiffness on the failure mode of a rockmass. Salamon (1970) demonstrated the concept of the interaction of a rock specimen and a testing machine. The experiment showed that the post-peak portion of the stress-strain curve of a compression test and the associated progressive failure of a rock sample depend on the relative stiffness of the specimen and the testing machine (Zvarivadza, 2015). Two scenarios are expected during the loading of a pillar support system, upon reaching the post-failure state (Guy, et al., 2017):

- I. If the stiffness of the loading system (K_M) is less than the post-failure stiffness of the structure (K_p), the system as a whole becomes naturally unstable because the structures’ load-bearing ability decreases at a faster rate than the loading system, often failing abruptly. The surrounding

rockmass deforms faster than the coal pillars, releasing energy into the support system. The energy of the system that is higher than the energy obtained in the pillars is converted either into sound or kinetic energy. Inevitable failure is expected to cause catastrophic failure if the unstable state remains.

- II. If the stiffness of the loading system (K_M) is greater than the post-failure stiffness of the structure (K_p), the system fails in a stable manner, irrespective of the load-bearing ability of the structure being exceeded. The loading system compresses the support system gradually, with time. Contrasting the unstable system, the structures lose the load-bearing ability at a slower rate than the loading system, maintaining post-failure equilibrium.

Therefore, a support system is deemed to fail in a stable manner, where the $K_p > K_m$ and unstable where the $K_p < K_m$.

For the post-failure condition to exist, it is required that the applied load exceeds the maximum load-bearing capacity of the system or a structure. This condition is required for the structure to remain naturally stable irrespective of the characteristics of the loading system.

From this analogy three alternative approaches were developed as a measure to prevent coal pillar collapses (Zipf, 2012):

- Containment approach

Pillars may fail violently in an unstable manner but are controlled by the barrier pillar as they exceed the strength criterion. The $FOS > 1$ but the Factor of Stability < 1

- Prevention

This case prevents any type of pillar failure from occurring. To satisfy this scenario both criteria should be satisfied: $FOS > 2$ and $W/H > 3$ or 4

- Full extraction

This scenario avoids pillar failure by total closure and full subsidence upon retreat mining. However, this will not be considered for the purpose of this study as subsidence is not an option. The area where the No. 2 seam is mined uses bord and pillar mining. Typically, this method aims at preventing subsidence as the overlying areas consist of farms and residences.

Limitations of the factor of stability

The limitations of this technique are that it requires substantial data to validate the findings (Zipf, 2012) which may not be available at the mine for the time being. Regardless of this, it presents the opportunity to redefine the stability criteria used in the coal industry providing a better way to ensure safety and optimal extraction.

2.6.5 Pillar width to height ratio

The use of the ratio of pillar width and height has provided a quick estimation of stability within mining in relation to a pillar's strength, however, is not formally used singularly, like the FOS, to help validate pillar stability as part of a combined system stability criterion (Guy, et al., 2017). As previously discussed in Section 2.5.2, it often describes the failure mode of pillars depending on the value of w/h as it transitions from brittle to quasi-ductile failure. The w/h ratio is mentioned by Guy et al. (2017) to be included into a systems' stability criteria, as it relates to the post-failure stiffness of the pillar.

2.7 Summary

The estimation of stability of a support system remains undeniably the most difficult part of support design. It establishes the extraction ratios and essentially the entire design of a mining layout. The choice of the techniques used depends on the available data in the area of investigation, leaning towards using more probabilistic methods to estimate stability particularly when analysing older working areas. Where data is substantiated such as within the Witbank area, empirical and analytical techniques developed specifically for that area would be preferred. However, this does not limit to those type of empirical methods and is up to the industry to provide further research to improve coal mine design as a whole. By understanding the limitations of the methodologies used and the influencing factors within the areas mined, successful secondary extraction can be achieved.

To fully grasp which methods of stress-strain analysis techniques would be best suitable for coaling at the No.2 Seam from this chapter, the following chapter will investigate an area where probable coaling is expected and has taken place.

Chapter 3: History of the investigation area

3.1 Mine background

Goedehoop, previously known as Springbok colliery (South), was developed in 1946 (AngloAmerican (Thermal Coal), 2015). In 2005, the colliery merged with Bank colliery (North) forming Goedehoop South and Goedehoop North. The colliery consists of three underground mining complexes being: Hope, Vlaklaagte & Simunye. From the three mining complexes, the investigation area chosen was Simunye shaft located in Goedehoop North, as shown by the shaded purple area in Figure 3.1-1. Simunye shaft is currently the only area that provides access to the No.2 Seam within the colliery.

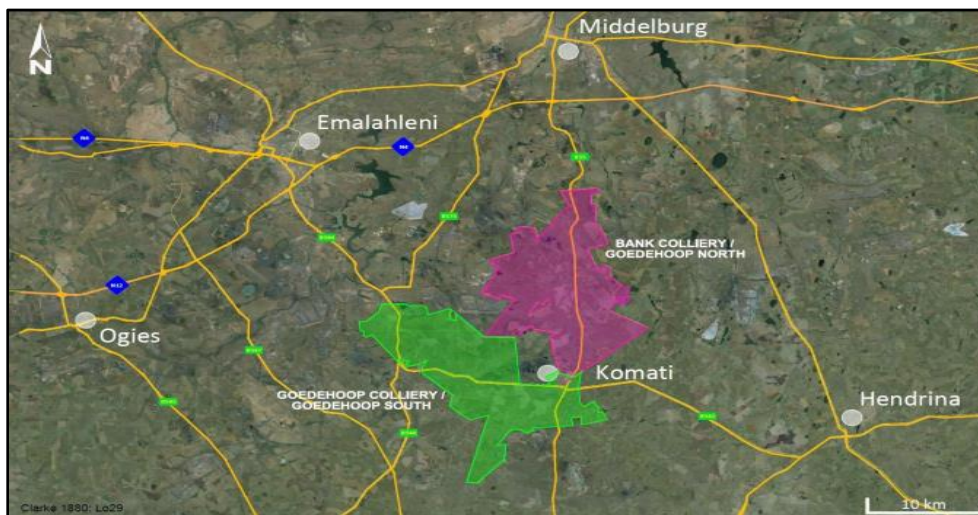


Figure 3.1-1- Locality map of Goedehoop colliery (Jones & Wagener, 2016)

There are four economically feasible coal seams in the leased area, namely the No. 1, 2, 4, and 5 Seams depicted in Figure 3.1-2, located within the green box (AngloAmerican (Thermal Coal), 2015). To date, the colliery has all mining rights of the seams. The majority of the No. 2 (mined in conjunction with the No.1 seam) and entire No.5 Seam have been previously mined. Presently, only a small portion of the No. 2 Seam reserves remain for primary extraction at Simunye shaft. It was estimated that approximately 2.7 Mt of run-of-mine (ROM) remains, with an expected life of 3.5 years (AngloAmerican (Thermal Coal), 2015).

The potential reserves that remain for secondary extraction are found in the northern and western regions of Simunye shaft. The current bulk of the mining operation is concentrated at the No. 4 Seam which comprises of 9 out of the 10 sections in operation with a current life of 18 years (AngloAmerican (Thermal Coal), 2015).

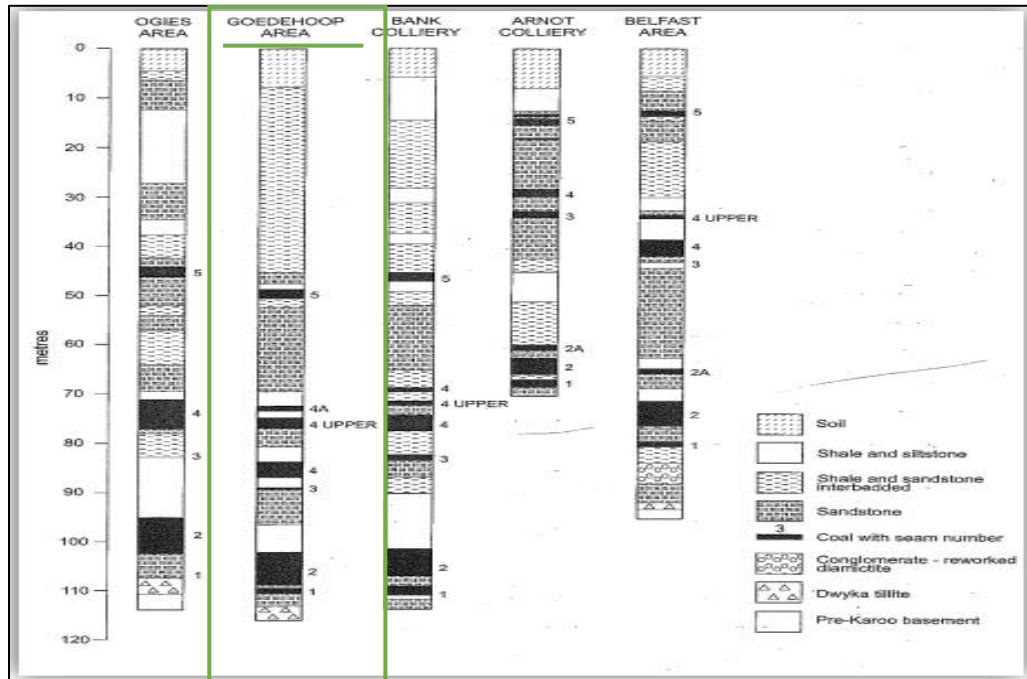


Figure 3.1-2- Stratigraphy columns in the Witbank coalfield (where the green box indicates the stratigraphy specific to Goedehoop) (Snyman, 1986)

3.2 Mine layout at the No.2 Seam

The area consists of irregularly sized pillars that vary significantly in effective width and height. The pillar size range observed was between 16 m and 18 m centre to centre (C2C) distance. In most cases the larger the centre to centre distance, the greater the pillar height. It is expected that where pillars are shorter in height more coaling may take place, considering that the maximum height at the No.2 Seam, as previously mentioned in Chapter 1, was about 6m.

Throughout the area where the site visit took place, there was observed deterioration of the pillars with time. This deterioration resulted in pillar loading, mainly due to scaling. The scaling generally occurred from the corners and perimeter of the

pillars. Pillars with a greater C2C i.e 18 m, tended to scale more, reaching an almost hourglass shape as demonstrated in Figure 3.2-1, whilst those that were narrow, barely scaled. The volume quantity of the scaled coal surrounded some pillars, providing some form of confinement, as depicted in Figure 3.2-2.

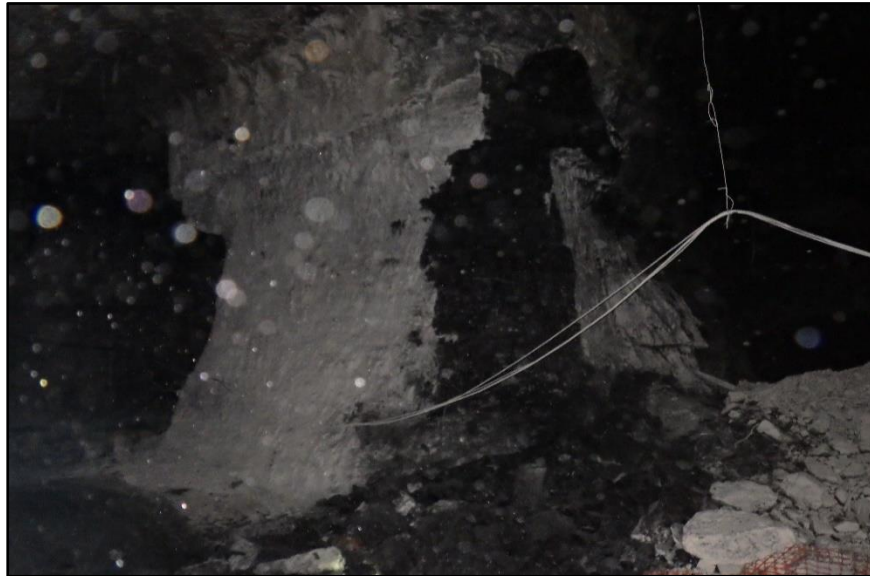


Figure 3.2-1- Hourglass shaped pillar formed by scaling at the No.2 Seam in Goedehoop colliery (*AngloAmerican (Thermal coal), 2017*)



Figure 3.2-2- Scaled coal surrounding a pillar at the No.2 Seam in Goedehoop colliery (*AngloAmerican (Thermal coal), 2017*)

Typical failure along the ribs (slip) of the pillars was observed as shown in Figure 3.2-3. Often large chunks of the pillar rib failed, especially in the presence of discontinuities like joints, greater than a metre in length. Roof failure was minimal due to the installation of roofbolts. At present, only one area exists where some of the pillars in a panel have failed, which is located South of Vlaklaagte (Goedehoop South) at the No.2 Seam.



Figure 3.2-3-Observed slip failure along pillar rib at No.2 Seam, Goedehoop colliery (*AngloAmerican (Thermal coal), 2017*)

3.3 Mining method used at Goedehoop Colliery

Bord and pillar mining has been the predominant primary mining method employed for coal extraction since production commenced at Goedehoop Colliery in 1946 (AngloAmerican (Thermal Coal), 2015). This also includes stooping, as a secondary method of extraction, which has been done occasionally, on a very small scale at Block 8 and Hope (mining panels at Goedehoop) where it was deemed feasible (Jones & Wagener, 2016).

Initially, mining was carried out solely by conventional methods (drill and blast) until the introduction of mechanized mining using a continuous miner (CM) in 1998 (Jones & Wagener, 2016). The final volumetric extraction was assumed towards the maximum recovery of the available reserves, during primary development. This

meant that mining was done without any intention of bottom or top coaling nor any other secondary extraction methods.

3.4 Bottom or top coaling history at Goedehoop

Colliery

Prior to 2004, with the use of conventional extraction methods in areas where the seam height reached approximately 8m, mining of the full seam height was not feasible. This was a result of the restricted minimum regulatory mining height of 3m as stated in the Mines and Works Act of 1956 and later amended in the Mine Health and Safety Act No. 29 of 1996 (South African Legal Information Institute, 1997). In addition to the 3m, a further 1.5 m of coal in the seam floor was mined using the method termed “bottom coaling”. Whilst when mechanized mining was introduced, top coaling was done because of the ability to access the coal at a higher mining height using a continuous miner. This selective mining only aimed at increasing the tonnage recovered from the No.2 Seam where it was economically feasible.

The issue of instability that may exist for both bottom and top coaling at the No. 2 Seam are presented as (Galvin, 2016):

- Increased potential for pillar failure as a result of the progressive change in pillar stiffness. Pillars no longer support an equal overburden load, as the induced load exceeds the tributary area load;

The issue presented will be investigated throughout the report, to determine the probable behaviour of the pillars due to secondary extraction and its effect on the loading environment.

3.5 Summary

Goedehoop colliery contains the mining rights to four coal seams, being No.1, 2, 4 and 5. Of the four seams, only three are being extracted – No.1, No.2 and No.4

Seams, where Seam No.4 currently provides 90% of the coal reserves being sold. To ensure safe and economical extraction, the mining layout and history were reviewed that would affect the rock engineering design of pillar support. From the review, it showed that the mine used two mining methods: conventional (drill and blast) and mechanised coal extraction (using continuous miner), where the latter was introduced 52 years after the start of the mine life. Final extraction throughout the area did not have the initial intent to include secondary extraction or retreat mining, hence 4,5m was mainly mined due to economic reasons. However, other secondary extraction methods which include pillar stooping and coaling were applied, when deemed feasible by the mine, particularly upon the introduction of mechanised mining.

Using the knowledge and observations made throughout the investigated area, a methodology was developed in the following chapter to help determine whether or not pillars will remain stable once coaling has taken place.

Chapter 4: Determining pillar loads and pillar strengths to evaluate pillar stability for secondary extraction

4.1 Introduction

The general consensus to determine support stability is to ideally estimate a probable factor of safety values within a region that is investigated. The procedure to determine pillar stability, which includes estimating values of Factor of Safety, Probability of Failure and Probability of Survival, once coaling has taken place, is demonstrated in the methodology hierarchy of Figure 4.1-1.

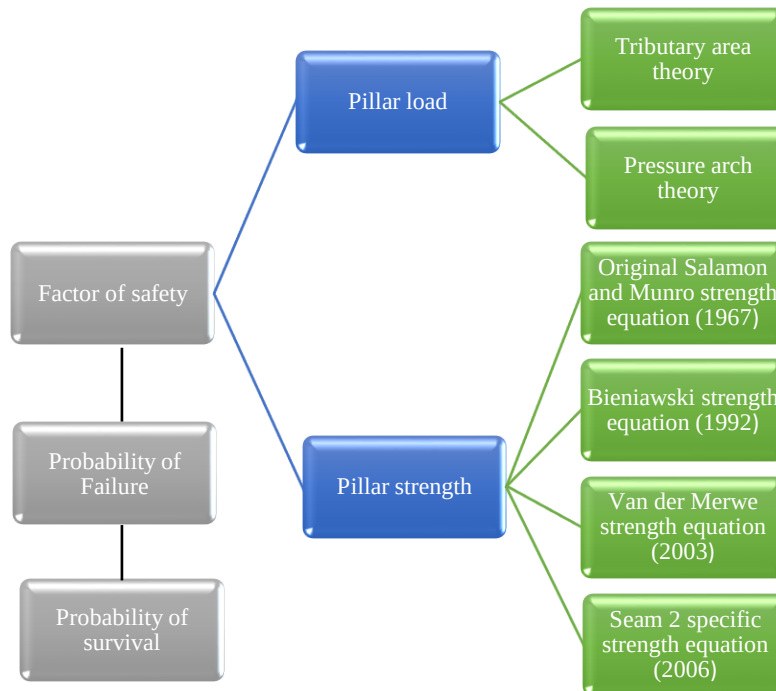


Figure 4.1-1- Hierarchy used to determine pillar stability for secondary extraction (coaling)

4.2 Determining individual pillar loads using the pressure arch theory

The Pressure Arch Theory (PAT) allows the determination of individual pillars loads, particularly of irregular shape and size, where the tributary area theory is not

applicable. A brief description of the theory itself and its principles is provided in Appendix A, Section 9.1.2. Unlike the TAT, the PAT assumes that each individual pillar has a different load-bearing capacity depending on its spatial position within a panel, geometric dimensions and depth of cover. This, in turn, determines the load transfer distance of which pillars within the region would share the overburden load amongst each other.

To analyse the stability of the pillars after coaling (top/bottom), a panel within the No.2 Seam was evaluated whereby coaling previously took place as shown in Figure 4.2-1(a), within the yellow circle. From the panel, 40 pillars were assessed to determine their individual loads using the pressure arch theory and tributary area theory. Additionally, pillars were evaluated according to the overburden depth. Two main depths were considered – 70m for the blue box and 75m for the red box shown in Figure 4.2-1(b).

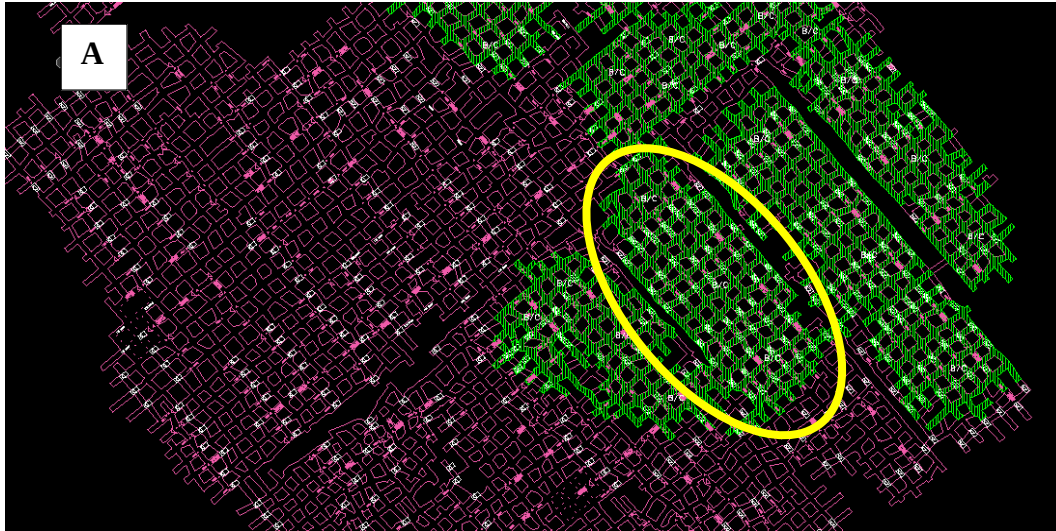


Figure 4.2-1- Panel where coaling has previously taken place and the pillar analysed, where (a)- coaling panel chosen and (b) the pillars chosen for the investigation (AngloAmerican (Thermal coal), 2017)

To determine the individual pillar loads using the pressure arch theory, three main equations were used:

Equation 4.2-1- Effective pillar width

$$W_{\text{eff}} = \sqrt{Ap} = 4Ap/C \text{ (Wagner, 1980)}$$

Where: A_p – Area of the pillar (m^2)

C – Perimeter of the pillar (m)

Equation 4.2-2-Load transfer distance for individual pillar

$$LTD = -0.0001H^2 + 0,2701H \text{ (Poulsen, 2010)}$$

Where: H – Depth of mining (m)

Equation 4.2-3-Zone of influence for individual pillar

$$Zl=2LTD+W_{eff}/2$$

Where: LTD – Load transfer distance (m)

W_{eff} – Effective pillar width (m)

The overall outcome of the aforementioned equations is to determine the area of the zone of influence, which describes the area where a particular pillar would share its entire load. The determined zone of influence from the above equation would be the lateral distance from a cross-sectional view or the circular radial distance in a plan view, from a particular pillars' geometric centre, as shown in Figure 4.2-2 and Figure 4.2-3, respectively.

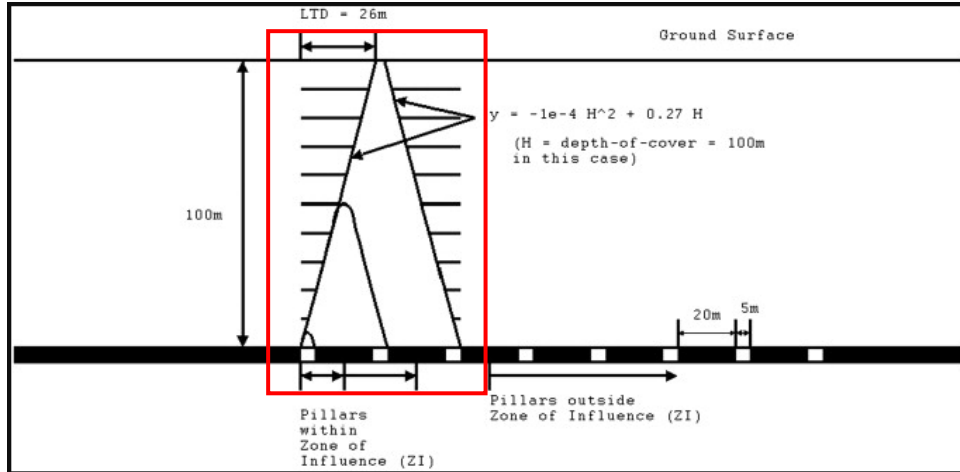


Figure 4.2-2- The load transfer between pillars in the pressure arch formed when a pillar is excavated in a coal seam (Poulsen, 2010)

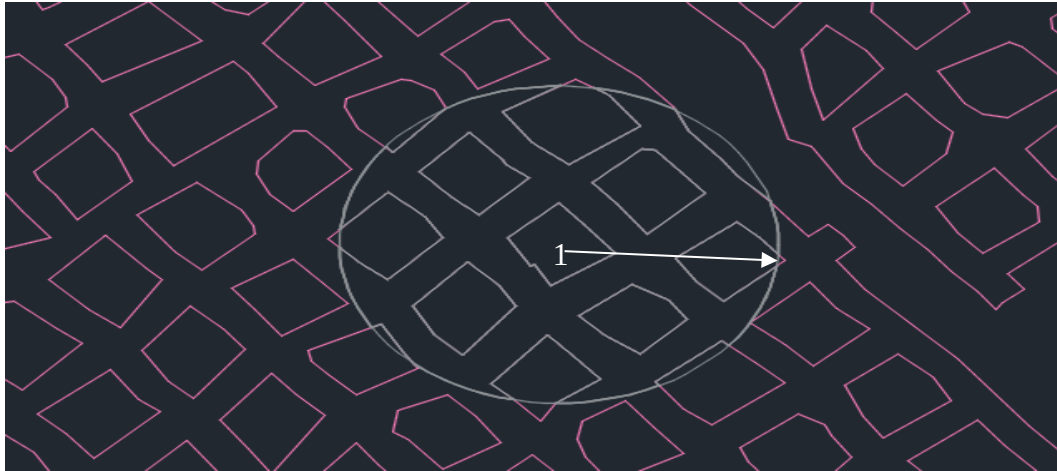


Figure 4.2-3- Circular zone of influence of a pillar within the No. 2 Seam

Using the average pillar stress in Equation 4.2-4; the individual pillar load was established.

Equation 4.2-4- Average pillar stress

$$\sigma_{APS} = \rho g H / 1 - e_1,$$

Where: ρ – Density of overburden- 2.540 t/m³

g – Acceleration due to gravity- 10 m/s^2

H – Depth of cover (m)

e_1 – Extraction ratio within the circular zone of influence

4.3 Determining individual pillar loads using the tributary area theory

Equation 4.2-4, was used to determine the pillar load from the tributary area. The total area of the individual pillars and the total area in which the pillars resided, was calculated to determine the extraction ratio. The pillar load value generated was determined at the specific depths and applied to all the pillars which resided within the depth contours, being 70m and 75m.

4.4 Determining pillar strength, FOS, POF and POS

To determine pillar strength, FOS, POF and POS, reference is made to the following equations in Table 2.5-1 of Chapter 2.

- Pillar strength: Three equations were used which are found in Table 2.5-1. The equations are (No.2) Salamon and Munro (1967), (No.3) Bieniawski (1992), (No.4) Seam 2 specific (Salamon, et al., 2006) and (No.5) Van der Merwe (2003) strength equations;
- Pillar FOS, POF and POS methodology and equations are provided in Section 2.6 of Chapter 2.

4.5 Assumptions

For the study, assumptions were made because the availability of data for each individual pillar was limited. The assumptions made were:

- The average mining height was 5.3m after coaling had taken place. This was determined from the difference between depths of five survey pegs that existed in the panel;
- The overburden depth to pillar roof or depth of cover was determined from overburden contours as shown in Figure 4.5-1. The contours determine the overburden throughout a section at intervals of 5m;
- The density of the overburden was chosen as 2.540 t/m³ from core logs obtained from the colliery;
- Coaling was done using drill and blast mining methods.

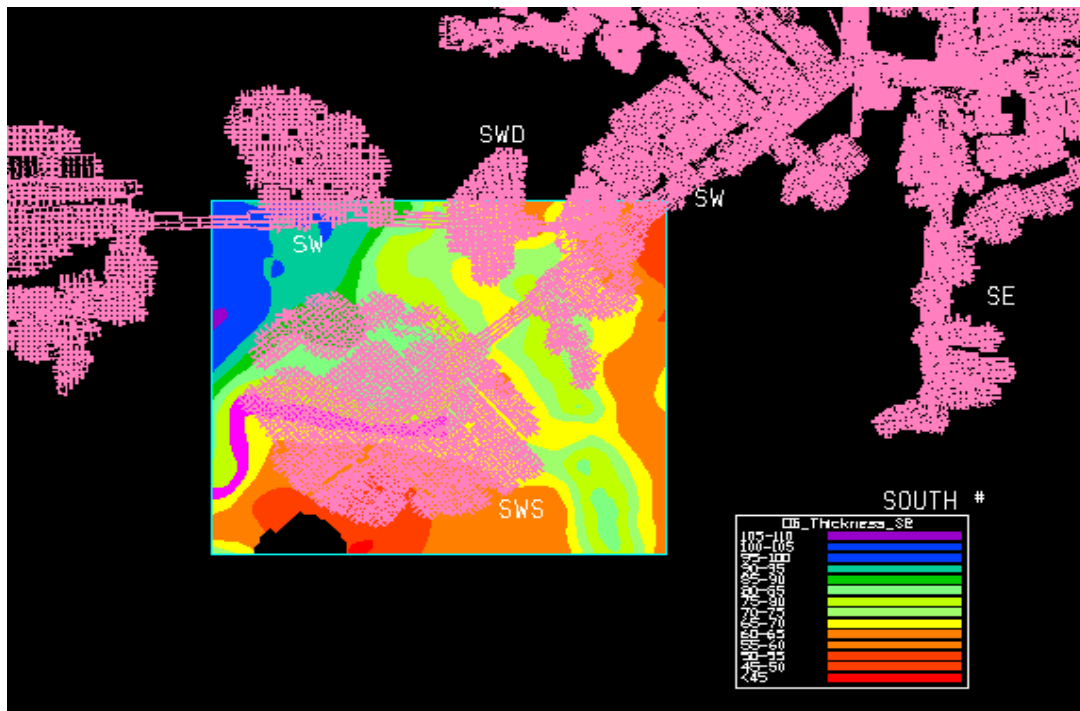


Figure 4.5-1- Overburden contours for a panel where coaling took place at the No.2 Seam (AngloAmerican (Thermal coal), 2017)

4.6 Summary

For the study, a panel was evaluated where previous coaling took place using drill and blast mining method. Within the panel, 40 pillars were assessed where bottom coaling had taken place, at different overburden depths. To establish the required parameters (pillar load and pillar strength) to estimate the stability of the pillars chosen, two empirical theories were used to estimate pillar load; the pressure arch

theory and the tributary area theory, whilst four strength equations, applicable to the No.2 Seam were used to determine the pillar strength. Where data was scarce for the individual pillars, a few assumptions were made: the first includes averaging the mining height from surveyed pegs once coaling had taken place (which in this case was bottom coaled), assuming an average overburden depth at an interval of 5m for the pillars within the contoured region and assuming the density of burden throughout the areas to be 2.540 t/m^3 from the core logs reviewed from the colliery.

Using the methodology shown in this chapter, the following chapter will present the results which will determine whether or not the pillars mined within this area will remain stable after coaling and is coaling feasible within this area.

Chapter 5: Results and discussion

5.1 Introduction

Forty pillars in a panel were assessed where previous coaling (bottom) took place, using two, 2-dimensional empirical stress-analysis methods. The stability of the 40 pillars was analysed according to their pillar load, calculated using the pressure arch theory and tributary area theory, whilst the strength of the pillars was estimated according to the 4 applicable strength equations at the No.2 Seam. From the two estimated parameters, the individual FOS, POF and POS of the pillars were estimated to establish which pillars would remain stable succeeding secondary extraction. The results were presented in graphical form in this chapter, whilst the individual pillar Xcel results are provided in Appendix B.

5.2 Average pillar stress using the pressure arch theory

The majority of the pillars found in the panel were calculated from a depth of 70 m, hence the bulk of the pillar loads reside between 4.0 and 4.3 MPa, which lies within expected values. At a greater depth, e.g. 75 m, from pillar No.30-33, 36-38, shown in Figure 5.2-1, there was a slight increase in pillar load values to about 4.7 MPa, which was expected, given that the vertical stress (in the vertical principle axis) is proportional to depth.

The general trend showed that for a row of pillars, as one moves further away from the edge of the panel i.e. barrier pillar, the pillar load value increases. This is best illustrated in Figure 5.2-1, e.g. from pillar No.5 to 11 (refer to Figure 4.2-1). The difference between pillar loads from the middle of the panel towards the edge of the panel is +/- 20%. From this study, it is possible to interpret the importance of a pillars spatial position with respect to its load-bearing capacity. Thus, in terms of practical design, smaller pillars, with smaller width to height ratios can be developed closer to barriers and larger towards the centre, ensuring an even stress distribution throughout a panel and reducing the possibility of failure.

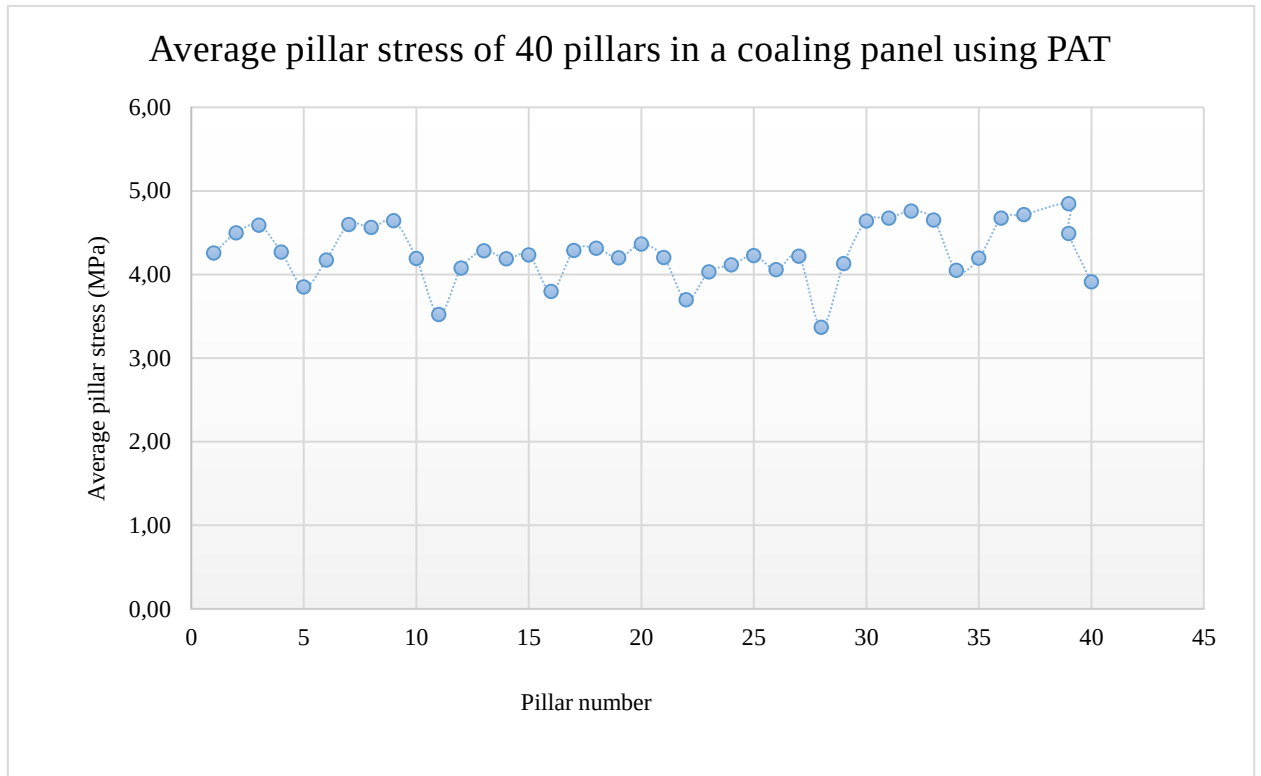


Figure 5.2-1- Average pillar stress of 40 pillars in a coaling panel using the pressure arch theory

Although the pressure arch theory provides a better estimate of pillar loads closer to numerical models developed to estimate pillar loading (Poulsen, 2010), the method is two-dimensional, thus ignoring the effect of stress in the lateral direction. More importantly, the theory assumes that the pressure arch formed over the pillar is symmetrical about the pillar's axis.

In the case where multiple seams are expected within the region, the arch is likely to be asymmetric (Hudock, 1983). Hence it is necessary to consider the effects of multiple seam mining on the actual stress distribution. Also, it is important to consider the relative stiffness of the rockmass, which affects the magnitude of the load carried by the individual pillars; the bridging capability of the overburden and the existence of inter-panel pillars (Van der Merwe & Mathey, 2013a).

5.2.1 Pressure arch theory pillar loads versus tributary area theory pillar loads

Calculating pillar loads using the tributary area shows a constant value of stress irrespective of the pillars spatial position in the panel as demonstrated in Figure 5.2-2. The load value calculated for the overburden depth of 70 m and 75 m were respectively given as 5.18 MPa and 5.55 MPa. The load value calculated using TAT tends to over-estimate pillar loads for irregular size and shaped pillars by 19%, as compared to PAT if one were to take the average pillar stress of 4.17 MPa using PAT. If the lowest value of stress is considered, e.g. 3.37 MPa from PAT calculations, it increases to 35%.

The stress difference between the two theories throughout the area is demonstrated in Figure 5.2-3. The average difference between the two theories is 1.04 MPa. The largest stress difference is observed for pillars closer to the edge of the panel and smallest for pillars closer to the centre as barrier pillar or solid pieces of coal that act as abutments, carrying the shared load of adjacent pillars.

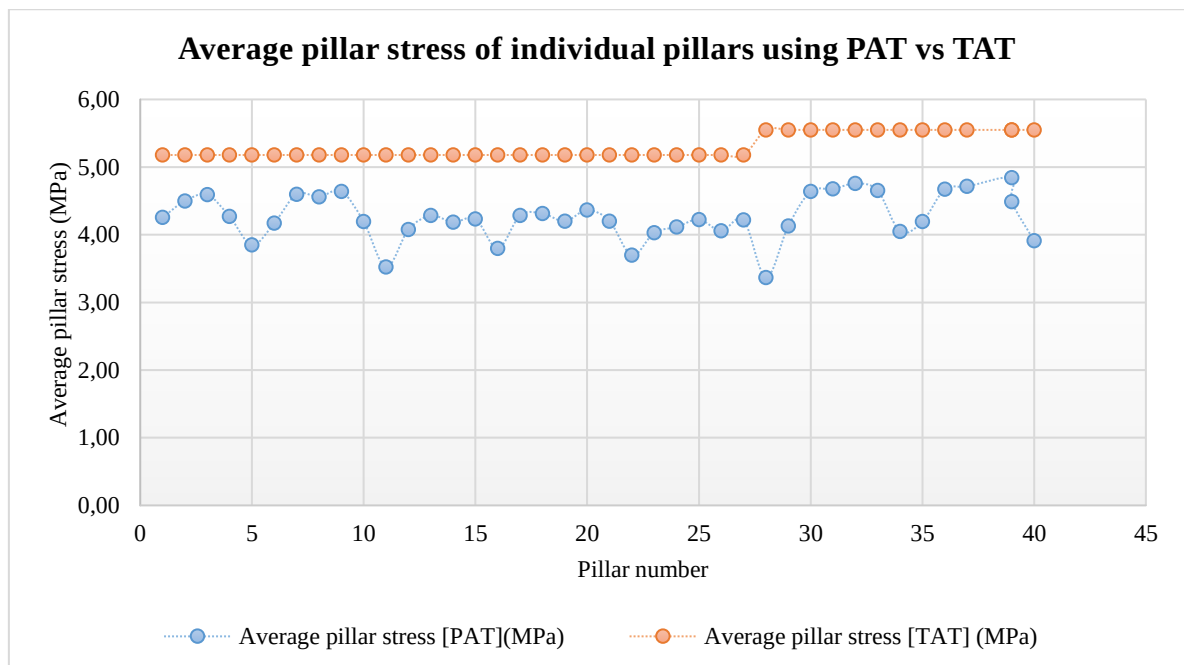


Figure 5.2-2- Average pillar stress in a coaling panel using PAT versus TAT

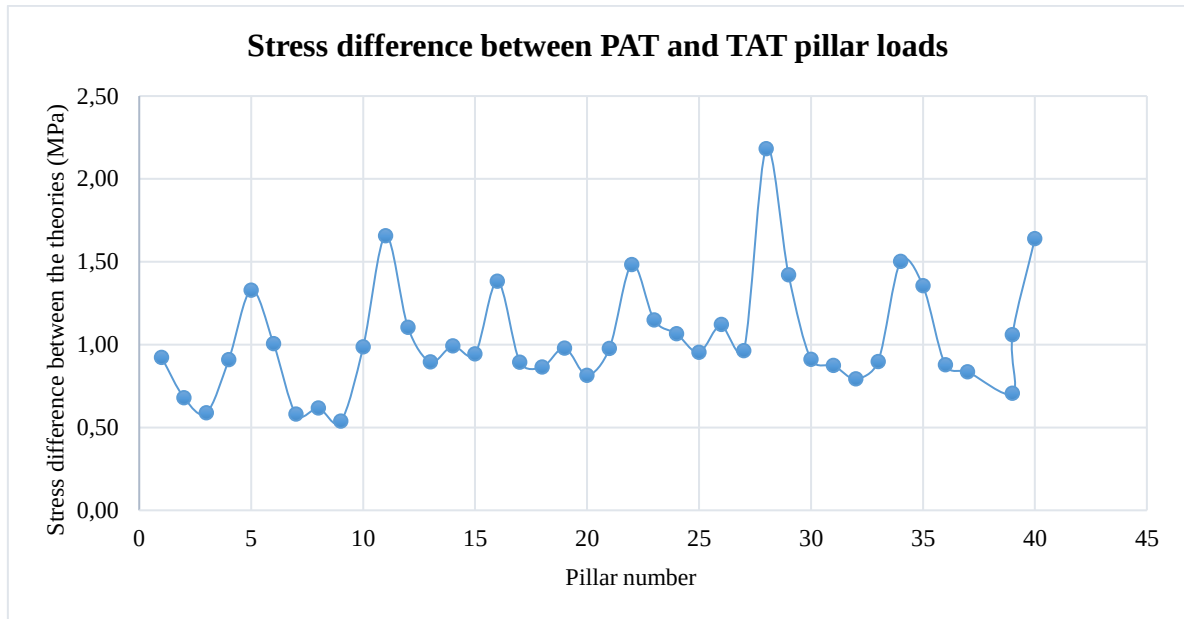


Figure 5.2-3-Stress difference between PAT and TAT pillar loads

5.2.2 Circular zone of influence effect on the average pillar's stress using PAT

From Equation 4.2-2 and Equation 4.2-3, the circular zone of influence is a function of depth (which remains constant for this research) and pillars effective width, respectively. For larger values of a pillars effective width, the zone of influence of which an individual pillar has widens, suggesting that a significant portion of a pillars load is shared. The implication of this, is that it reduces the actual load an individual pillar carries. Looking at Figure 5.2-4, a trend can be seen amongst the graphs whereby for higher values of individual pillar stress, the circular area of influence, which is a pillars' zone of influence, reduces. This indicates that, that specific pillar carries a greater load and less of its load is shared. This is more so for pillars further from the barrier pillars or positioned towards the centre of the panel.

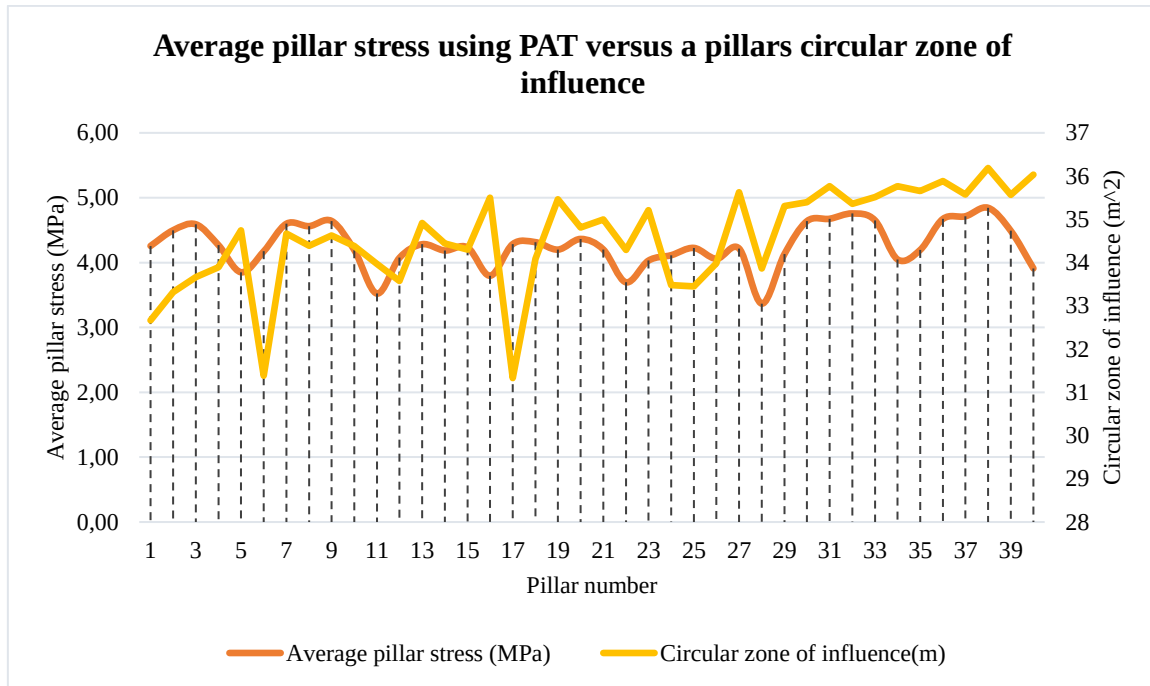


Figure 5.2-4- Average pillar stress versus a pillars circular zone of influence using PAT

5.2.3 The effect of extraction ratio on a pillars average stress using the pressure arch theory

The extraction ratio using the pressure arch theory averaged at 57.5%, whilst a value of 65.7% was estimated using TAT for the 40 pillars, both which reside within the 75% limit. The value difference of extraction ratios between TAT and PAT is a result of the exclusion of barrier pillars from the calculation of the coal extracted in TAT. Therefore, it is expected for TAT to have a higher extraction ratio value given that it uses average pillar widths and centre to centre distances in a panel. Whereas using PAT, the extraction ratio is determined for each individual pillars circular zone of influence and then the extraction values are averaged including that of the barrier pillar, demonstrated in Figure 4.2-3 and Appendix B (Section 8.1.1).

Pillars closer to the centre showed higher extraction values whilst those closer to barriers were lower, as expected. Also, where some pillars were larger, where probable difficult ground conditions were encountered less coal would be extracted, reducing the overall extraction ratio within the pillars circular zone of influence.

Figure 5.2-5 shows that pillar stress and the coal extracted share a similar behaviour, almost identical in shape, therefore, sharing a proportional relationship that the higher the pillar stress the higher the extraction ratio within a pillars circular zone of influence. This applies specifically in plan view or in a 2-dimentional analysis and to the pillars located in the centre of the panel. Furthermore, this would not apply to top or bottom coaling which accounts for a change in the third dimension being a pillars height.

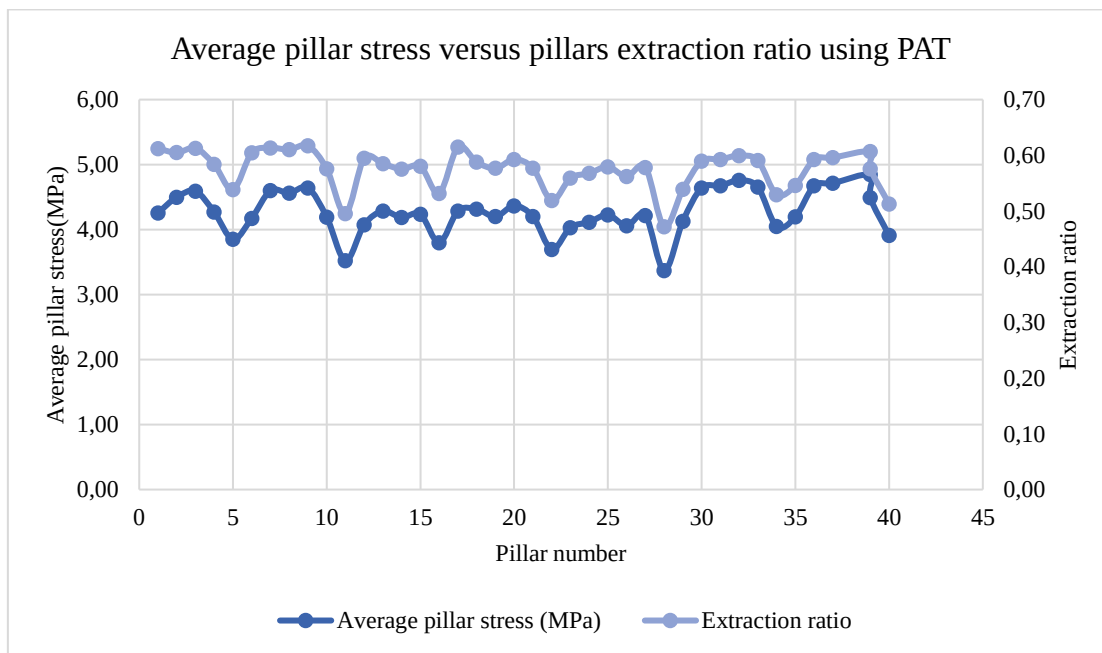


Figure 5.2-5- Average pillar stress versus pillars extraction ratio using PAT

5.2.4 The effect of w/h ratio on pillars average pillar load using PAT

The bulk of the pillars studied were above the w/h ratio of 2, with only 2 out of the 40 pillars having a value of 1.8. The two pillars from the 40 pillars reviewed were the lowest in terms of effective width, both at a value of +/- 9.4m. The two pillars with a w/h ratio less than 2 should be reviewed for possible instability. On average the width of the pillars was about 12.7m, with the exception of the two smaller pillars.

From Figure 5.2-6, as the pillar width to height ratio increases the pillar load carried by an individual pillar decreases. This indicates that the stiffness of the pillar is affected by the value of the width to height ratio. Pillars would thus have a greater load-bearing capacity, for a higher w/h ratio value as it increases a pillars ability to resist deformation (refer to Appendix B, Section 8.1.2), as previously discussed in Chapter 2.5 of pillar size and shape.

Using the TAT, shown in Figure 5.2-7, it is difficult to interpret the effect of load on individual pillars w/h ratio, since the pillar load remains constant throughout. Van der Merwe & Madden (2010), argue that by averaging values in support design it eliminates the variability of risk and stability by using a constant value within an a layout, shown by the example of the TAT and w/h ratio in this section.

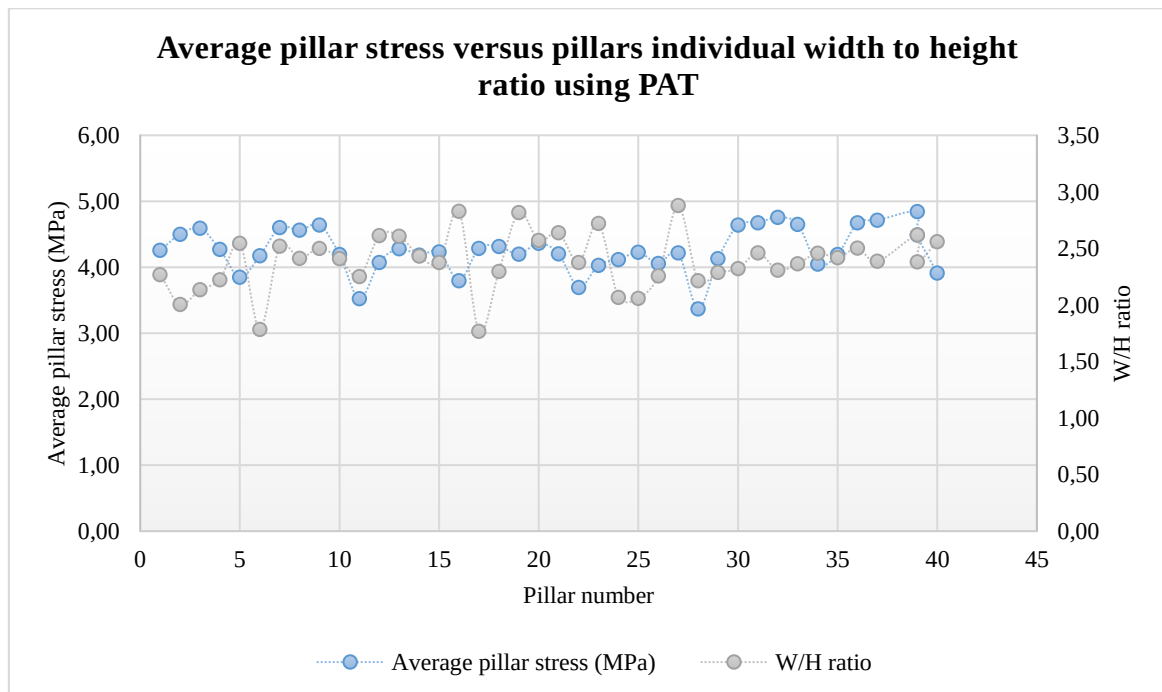


Figure 5.2-6- Average pillar stress versus individual pillar width to height ratio using PAT

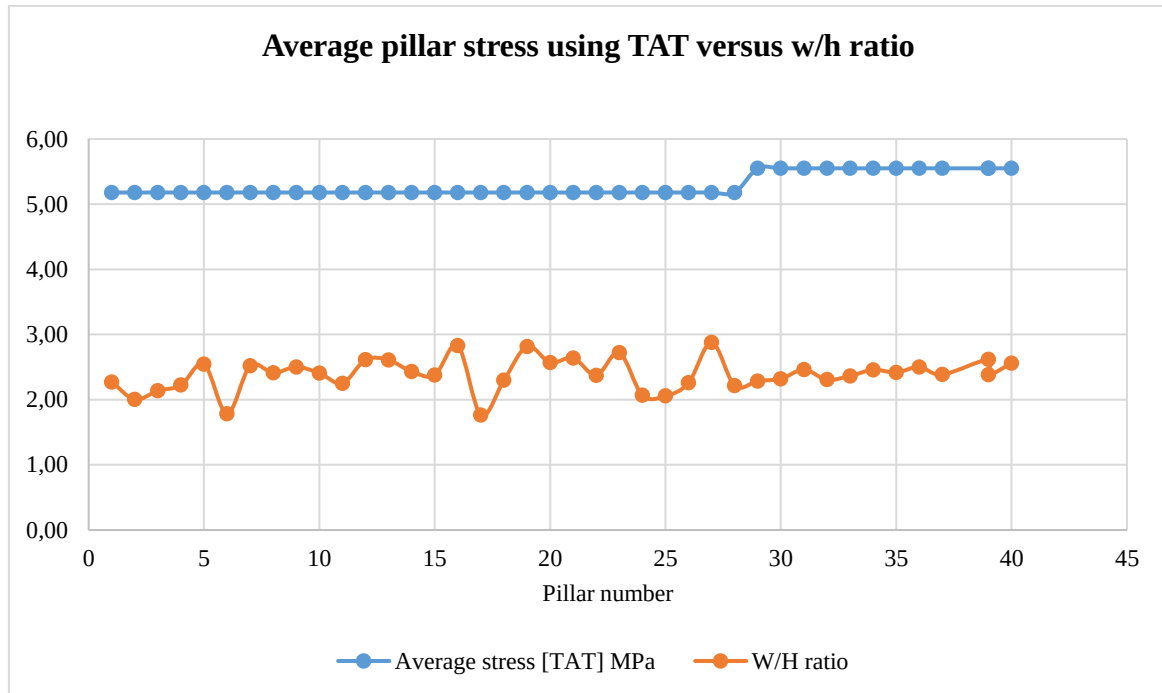


Figure 5.2-7- Average pillar stress versus individual pillar width to height ratio using TAT

5.3 Average pillar strength using 4 empirical equations applicable to the No.2 Seam

Individual pillar strengths were calculated using their effective pillar width and an average mining height of 5.3m, from 4 empirical equations mentioned in the previous chapter. The strength of the pillars is graphically represented in Figure 5.3-1. The lowest strength values were predicted from Bieniawski's strength equation whilst the highest can be estimated from Van der Merwe's. Interestingly, both are linear strength equations.

A possible reasoning to Bieniawski's strength values may be contributed by the use of direct strength measurement from a specific mine to estimate coal strength, which limits its applicability to other geotechnical regions and only using 27 cases of failed pillar workings for the statistical analysis, of which is known to have increased to almost three times the value to date (Van der Merwe & Mathey, 2013a). Additionally, Van der Merwe's strength value may be contributed by its use of an

updated database of failed and intact pillar case, of which is more recent and may show a realistic statistical trend than the other three strength equations.

Overall, high strength values were estimated for pillars with larger effective widths. It would be expected that where pillar height increases, pillar strength would decrease given a constant effective pillar width, however for this study the pillar height was kept at the average extracted. This was due to the lack of survey pegs within the area to determine any height differences and without accessibility to the area, actual measurements could not take place.

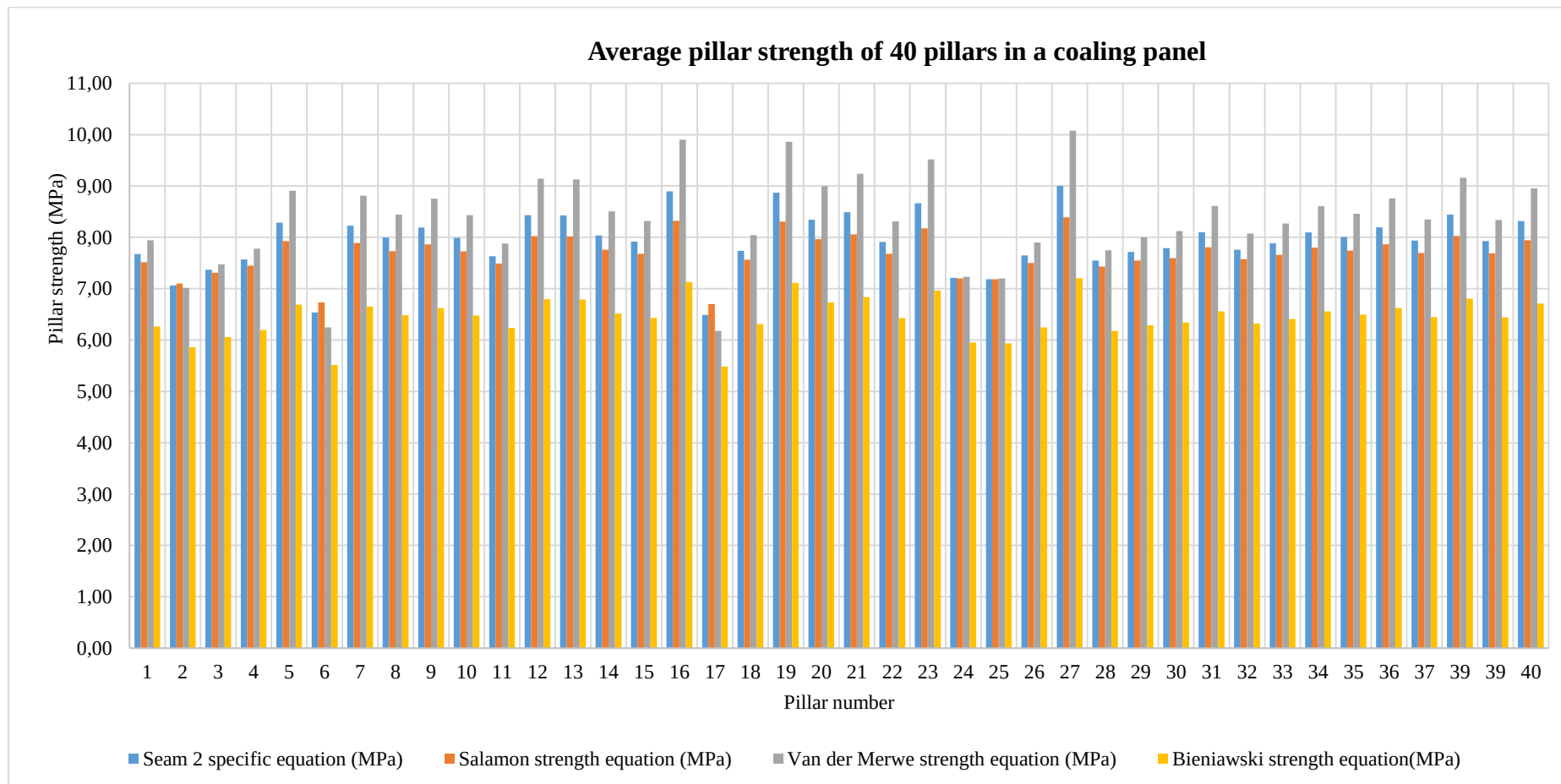


Figure 5.3-1- Average pillar strength of 40 pillars in a coaling panel

5.4 Stability prediction of pillars in a coaling panel

5.4.1 Estimating FOS using PAT and TAT

Stability of the individual pillars was predicted using the FOS, POF and POS for both the pressure arch theory and tributary area theory. The pillars evaluated were where previous coaling took place and which were identified as stable. From the pressure arch theory, stability was predicted for all pillars using the Salamon and Munro formulae (1967), Van der Merwe (2003) and Seam 2 specific equation (Salamon, et al., 2006), residing well above 1.6 depicted by the black line in Figure 5.4-1. However, instability was predicted for the majority of the pillars using Bieniawski's (1992) equation shown.

The average factor of safety value estimated for the area was given as 1.8, 2.0 and 1.9 for the three aforementioned equations, whilst 1.5 was estimated using Bieniawski's (1992) equation. One or two pillars were identified as possibly unstable from the Seam 2 specific equation (Salamon, et al., 2006) and Van der Merwe (2003) equation, whilst all were considered stable using Salamon and Munro's (1967) formula. The data is presented in Figure 5.4-1. For lower values of pillar load, the FOS of the pillars was larger. Again, this would be expected from pillars closer to barrier pillars than those in the centre.

From Figure 5.4-2, the tributary area theory estimated that 80% of the pillars are unstable using Seam 2 specific equation (2006), 95% using Salamon and Munro's formula (1967), 62.5% using Van der Merwe's formulae (2003) and 100% using Bieniawski's (1992) equation. Overall, instability is predicted using TAT. This indicates how much the theory overpredicts the load on pillars, consequently assuming complete/catastrophic failure where at present has not occurred, as observed during the underground visit. The average FOS value predicted from the four aforementioned equations using TAT average pillar loads is given as 1.5, 1.46,

1.58 and 1.22 respectively. All the values are below the standard FOS of 1.6 for bottom coaling.

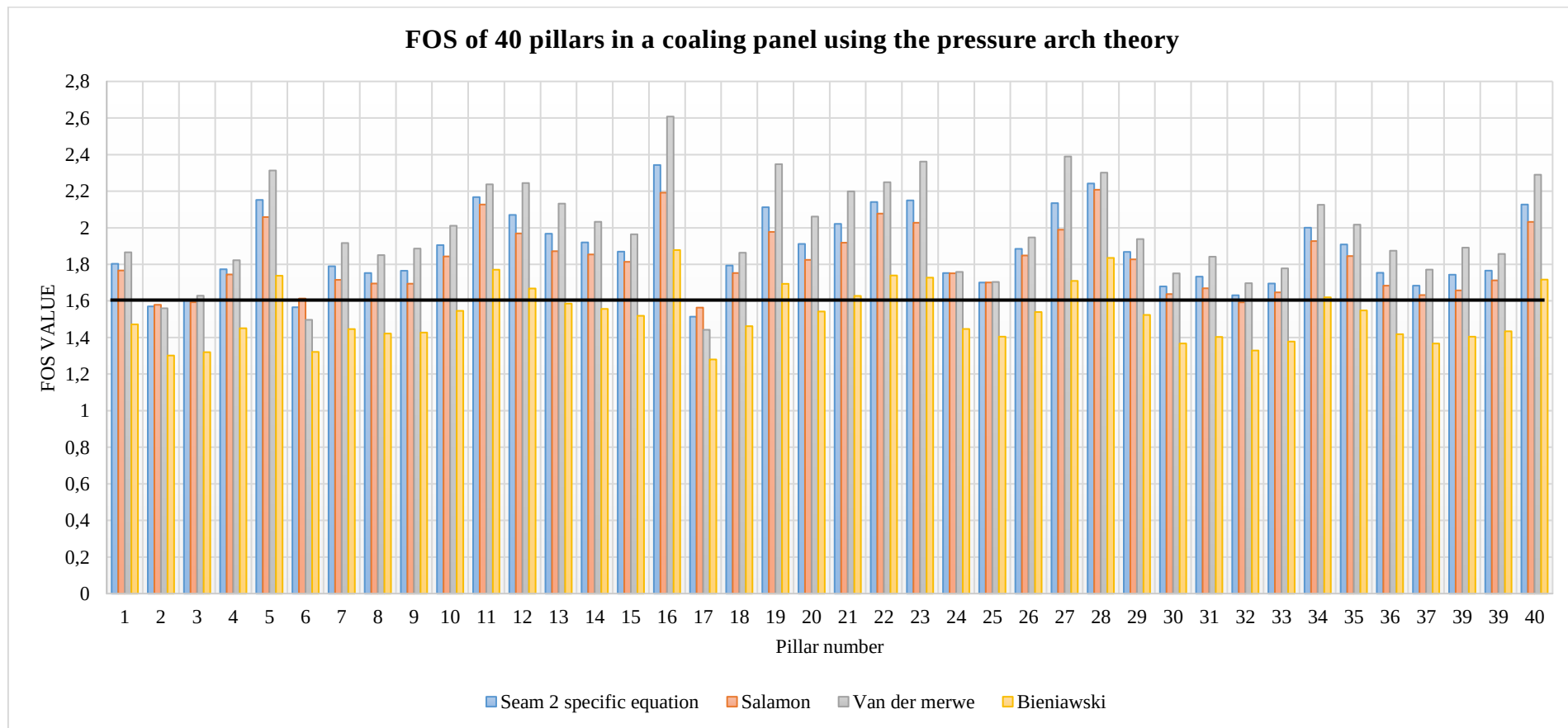


Figure 5.4-1- FOS of 40 pillars in a coaling panel using the pressure arch theory

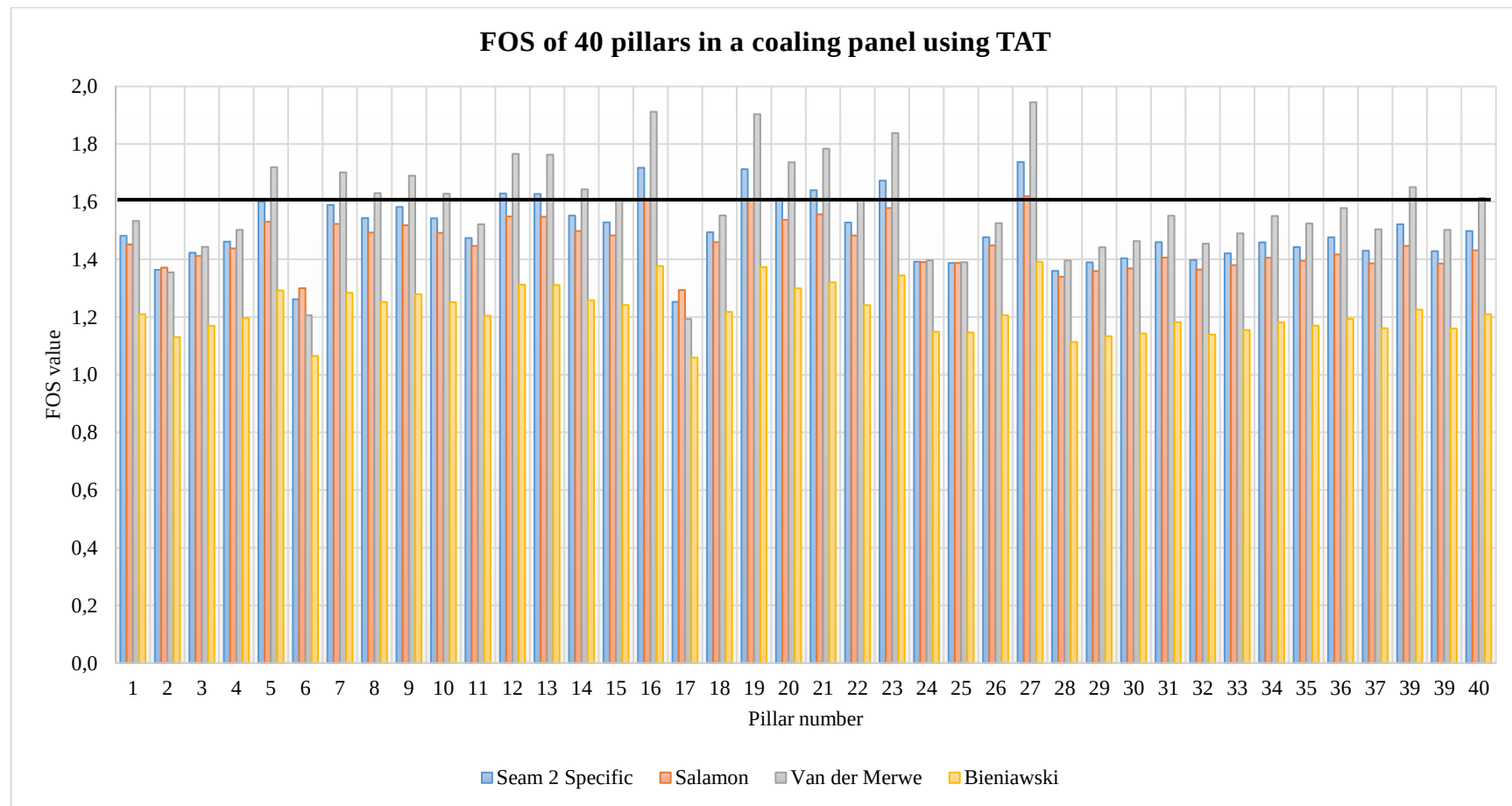


Figure 5.4-2- FOS of 40 pillars in a coaling panel using TAT

Prior to mining, the expected average mining height was 4.5m. By simply changing the mining height and maintaining each of the individual pillars circular area of influence, the FOS estimated were an average of 2.2, 2.0, 2.3 and 1.7, using PAT shown in Appendix B (Section 8.1.2). This provides an indication that coaling would have taken place at a lower FOS value from primary development than that suggested by Galvin (2016). To meet Galvin (2016), requirements the suggested mining height prior to coaling in that area would have to be 3.5m for the first three mentioned equations. Both results can be seen in Appendix B, Section 8.1.2

5.4.2 Estimating pillars probability of failure and survival

The probability of failure (POF) was estimated using Figure 5.4-3, whereas the POS was estimated by subtracting the value of POF from a hundred. Looking at the figure, the graph only extends to a FOS of 2.0, so for values higher than that, the POF was assumed to be equivalent to 0. Overall, from using the pressure arch theory, the pillars remain within their limits except for a few pillars below the black line in Figure 5.4-4, if Bieniawski's (1992) strength equation is used at a POF of 99% for production panel pillars. If structures are considered, which would in some instances a value of 99, 99%-99, 9995% is required. In which in this case include some pillars in all four equations, shown in Appendix B.

Figure 2.6-2- Probability of failure versus factor of safety

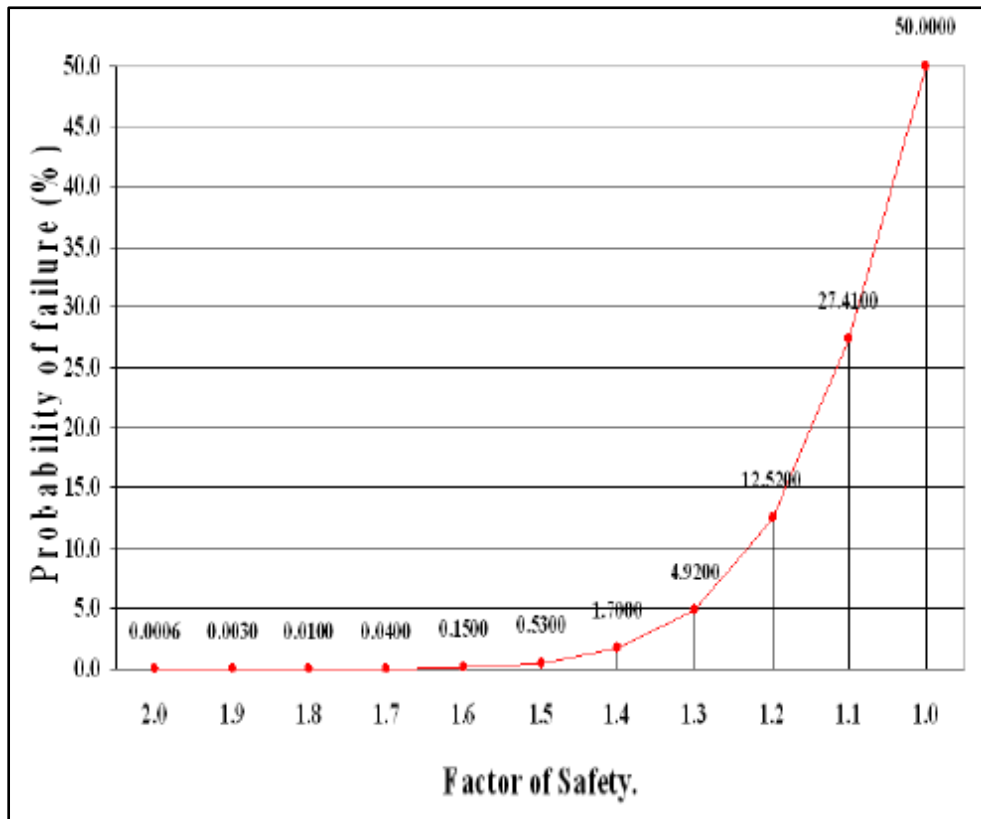


Figure 5.4-3-Probability of failure versus factor of safety (Brady & Brown, 2006)

Contrastingly, Figure 5.4-5 shows that using TAT, a significantly greater portion of the pillars would not survive succeeding coaling, indicated by the columns below the black line. This indicates the possibility of complete pillar failure and subsequently a panel collapse which may sterilize reserves that exist at the No.4 Seam, which overlay the No.2 Seam. Appendix B, Section 8.1.3 shows that all pillars would not survive as required within the limitations of a production panel and if surface structures exist, when using Bieniawski's (1992) strength equation. Probable failure of one or two pillars has stark implications on the ability to mine and ventilate hence the values presented using the TAT should provide a warning even if it tends to overestimate irregular pillar loads.

The accuracy of the results could be improved if direct measurements were made within the mine since the factor of time has not been considered. It would be likely

that scaling of the pillars would have occurred. However, the extent of this scaling is not certain. More importantly, the limitations of the empirical methods must be considered such that it affects the quality of the results. Alternatively, numerical modelling can be performed to account for the rockmass parameters on the effect of pillar load, probable scaling rate of pillars as mentioned previously in Chapter 2 and which coaling method would be best fit for the area. Overall, it would be safe to predict that the pillars would remain stable. The FOS values predicted reside above the highest limit for coaling of 1.6, using PAT. Therefore, it would be possible to coal in this area granted that PAT is applied prior to possibly mining the area.

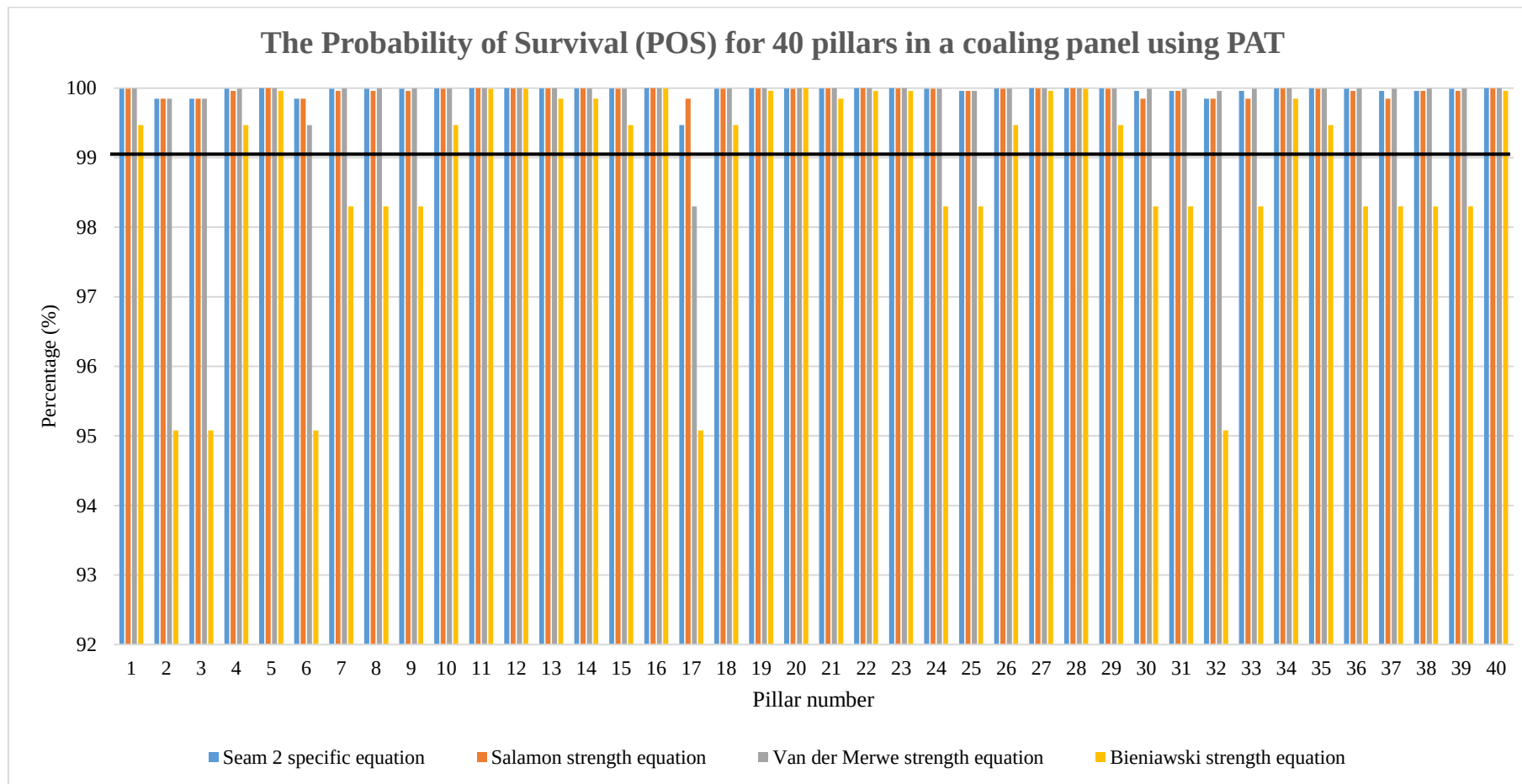


Figure 5.4-4-The probability of survival for 40 pillars in a coaling panel using PAT

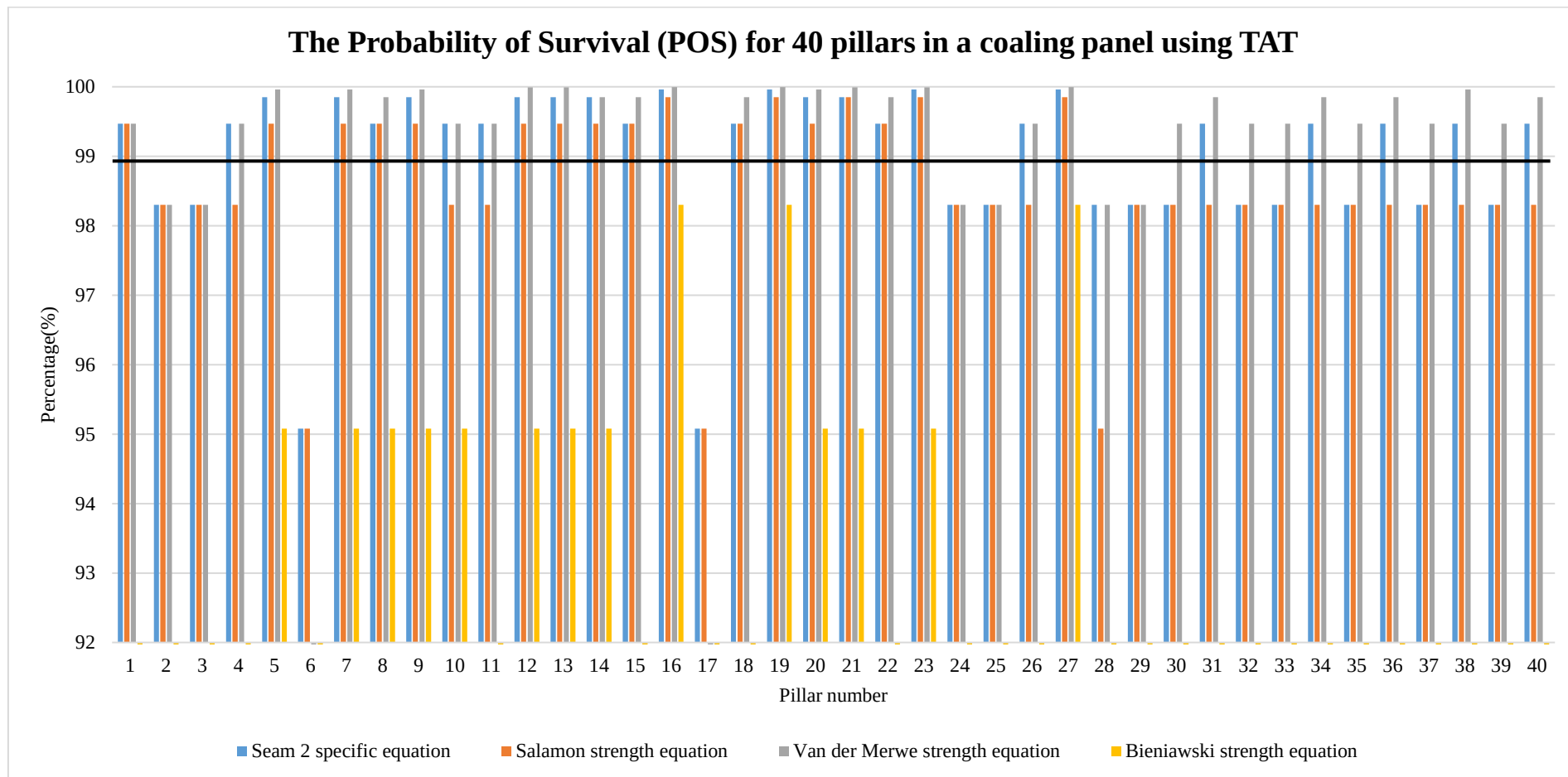


Figure 5.4-5- The probability of survival for 40 pillars in a coaling panel using TAT

5.5 Summary

Using two, 2-dimensional empirical stress-analysis methods, the stability of 40 pillars in a coaling panel was assessed. Two parameters were estimated to determine pillar stability, the first was estimating pillar loads using the pressure arch theory and tributary area theory. The second parameter included estimating pillar strengths, using empirical strength formulae applicable to the No.2 Seam; being the Salamon and Munro (1967), Van der Merwe (2003), Seam 2 specific (Salamon, et al., 2006) and Bieniawski (1992) strength equations.

The results from the study showed that the pressure arch theory estimated lower pillars loads for the individual pillars depending on their spatial position adjacent to solid abutments or barrier pillars whereas the tributary area theory assumed equal pillar load irrespective of the bridging effect, overburden stiffness and inter-panel pillars. In turn, from the strength values calculated, stability was proposed for the pillars using the pressure arch theory and instability for the tributary area theory. Moreover, the probability of failure and survival was estimated, and majority of the pillars remained within the limit of 99% expected for a production panel. Coaling can, therefore, be applied on the basis that the FOS estimated resides above the highest limit of 1.6, by using PAT.

Chapter6: Conclusions and recommendations

Predicting stability of pillars for secondary extraction (coaling) within the No.2 Seam remains difficult, primarily because the current empirical techniques used are based on old databases, of planned mined dimensions for primary extraction and there are no set rock engineering guidelines specific for coaling in the industry.

By reviewing existing knowledge within the coal industry with regards to pillar design, the shortcomings were presented which influences future designs. Four aspects of pillar design were considered, namely the pillar load, pillar strengths, stability criteria and methodologies to prevent catastrophic pillar failure. Of the four, pillar loading remains the least researched and overestimated, particularly since the tributary area theory dominates its use in the industry by its simplicity and ability to generate an answer within a short space of time. An alternative to TAT was provided, known as the pressure arch theory, which is a two-dimensional method that predicts individual pillar loads where the TAT does not hold e.g. irregular size and shaped pillars. However, it does exclude the effect of lateral stresses on pillar loads and lack credibility in use.

Similarly, pillar strength equations were reviewed that were applicable to the No.2 Seam and although the equations have demonstrated their reliability in providing safer working environments, post the Coalbrook disaster, over the past two decades coal research has been quite stagnant thus requiring further critique.

Overall, the results presented from using the pressure arch theory within a coaling panel (where coaling had already taken place) showed that 40 pillars would remain stable and within their limitations as expected from the FOS, POF and POS. The PAT and suitable stability criteria mentioned can be used as an alternative method to assess stability for secondary extraction from coaling, provided that sufficient data exist and is justified by alternative methods such as current stress measurements underground and numerical modelling. In addition, the research

identified the deficiency in TAT of overestimating a pillars load where coaling had already taken place and still remain stable, whereas TAT predicts otherwise.

The following recommendations can be considered from the research:

- Numerical modelling should be considered to compare the data generated from pillar values using the pressure arch theory in 2D and 3D;
- Monitoring of underground pillar deformation and stress measurements is required to establish the extent of failure;
- All influencing factors on pillar design must be considered and their effect on either pillar loads and pillar strength values within a layout;
- Additional stability criterions should be considered to assess further stability, particularly for secondary extraction;
- Data measurements of pillar scaling compared to pillar original size and the time of formation required at Goedehoop colliery, to determine the possible life of the pillars.

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Appendix A

7.1 Potential methods to estimate coal pillars loads

This section summarises the current empirical methods used to estimate coal pillar loads, their applicability to estimating pillar load at the No. 2 seam and the limitations of their use.

Tributary Area Theory (TAT)

The tributary area theory (TAT) has been the most common and quickest method used in the coal industry to estimate the average coal pillar load, as shown in Equation 7.1-1.

Equation 7.1-1- Average pillar load estimated from the tributary area theory

$$L = \frac{0.025 H w_1 w_2 C_1 C_2}{w_1 w_2} \text{ (Salamon \& Oravecz, 1976)}$$

Where: L- Pillar load (MPa)

0.025- typical overburden stress per meter in coal mining environment (MPa/m)

H- Depth of mining (m)

C₁ and C₂ - Centre to centre distance between pillars (m)

w₁ and w₂ – Pillar widths (m)

From Equation 7.1-1, the load generated by the full overburden is mainly a function of depth, pillar geometry and extraction ratio (Roberts, et al., 2002).

Application of the Tributary Area Theory

The tributary area theory is best suited at estimating the average pillar load when: The underground mine layout is designed uniformly, equal in dimension and the span of the individual panels is greater than or equal to the depth of mining (Brady & Brown, 1999). On grounds that the layout meets the criteria, the average uniaxial pillar load that each pillar will carry is equivalent to the weight of overburden immediately above it and one-half of the room's widths (Zvarivadza, 2015), as shown in Figure 7.1-1.

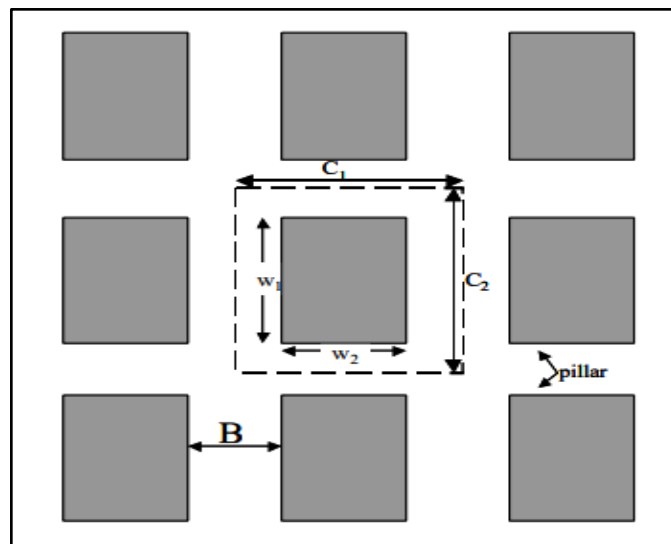


Figure 7.1-1- Plan view of the geometry used in tributary area analysis of pillars in uniaxial loading (Roberts, et al., 2002)

Limitations of tributary area theory

- The tributary area theory is seen as an oversimplified and conservative approach to estimating average pillar loads, particularly for flat dipping or shallow dipping seams, as argued by Van der Merwe (1998). The theory overestimates the average pillar stresses for

irregular geometries (Roberts, et al., 2002), potentially locking reserves in the support;

- Other factors that vary the load generated which have been covered include the influence of barrier pillars on the stress distribution, the pillar stiffness, overburden stiffness and bridging capability is ignored (Roberts, et al., 2002);
- The distribution of the vertical principal stress within a layout depends on the proximity of the pillars adjacent to one another (Hopkins, 1993). It is often necessary to consider their spatial interaction of pillars to evaluate the effect of the stress distribution on the behaviour of pillars;
- The theory restricts itself to the normal pre-mining stress and only applies the load to the vertical principal axis of each pillar. It thus assumes that all other stress components of the mining stress field have no effect on the pillar performance (Sankar, 2011).

Despite its limitations, where few accurate methods exist, the tributary area theory remains in use to estimate the average pillar stress whilst accounting for its limitations.

Pressure Arch theory

Application of pressure arch theory

Realistic bord and pillar underground mine layout consist of in-panel pillars that are arbitrary shaped and arbitrary positioned relative to one another. Given this condition, the pressure arch theory may be considered in the estimation of the average pillar load as it is applicable to non-uniform layouts, once mining has taken

place, particularly when the conditions of the tributary area theory are not met. (Poulsen, 2010).

Theory of the pressure arch

Unlike the TAT which is mainly used in the pre-feasibility stage of support design, the pressure arch theory considers the effect of the spatial relationship of the individual pillars relative to one another, to the variability of the load carried by each pillar. The load carried by each individual pillar depends on; the pillars spatial position relative to abutments, unmined seams, barrier pillars, seam dip and a varying bord width (Poulsen, 2010). The conceptual theory states that a pressure arch is formed by an excavation in a pre-stressed material. The pre-stressed material deflects slightly and relieves itself of the load of the overlying strata by transferring it to the sides of the opening forming a pressure arch (Chary, 2015). The stresses arch over the pillars (which include abutment stresses) at a distance away from the developed excavation, which acts as the zone of influence/load transfer distance (LTD) as shown in Figure 4.2-2.

Within the lateral load transfer distance, the overburden load can be shed/transferred between pillars, establishing the maximum distance that any effect mining may cause. Excavations developed outside the LTD will not share any stress and the full tributary area theory will be applicable to that individual pillar (Poulsen, 2010).

The load is estimated by determining how the redistributed load from the development of an excavation within an area, interacts with the surrounding rockmass to determine the stress within a pillar's zone of influence (A_1) (Poulsen, 2010), given by Equation 7.1-2 :

Equation 7.1-2- Average pillar stress for pillars within the excavated area of influence

$$\sigma_{v(LTD)} = \rho g H_p (2LTD + w_e/2)^2 / [p(2LTD + W_e/2)^2 - A_l] \text{ (Poulsen, 2010)}$$

Where: ρ - Average density of the rockmass strata (kg/m^3)

g -gravitational acceleration ($9,81\text{m/s}^2$)

H_p -Depth of mining relative to the individual pillar (m)

LTD- load transfer distance (m);

{Provided by Equation 4.2-2; where:

$LTD = -0.0001H^2 + 0,2701H$ (Poulsen, 2010) and H =Depth of mining (m)}

W_e – Effective pillar width (m)

A_l – Excavated area (m^2)

The load estimated from Equation 7.1-2 is only for a specific individual pillar that is being analysed, or rather the pillars that exist within the LTD. An advantage of this approach is its suitability for the automated analysis of hundreds of pillars, on a pillar to pillar basis, allowing the regular input of data to observe any variable stress changes (Poulsen, 2010). The pressure arch method of approach considers the plan shape of the pillar and layout which has shown to be beneficial when estimating pillar stress in comparison with a two-dimensional numerical approximation of the same layout. Furthermore, the prediction of the pillar's stress using this theory has shown to be in better agreement with a numerical modelling (2/3D), for pillars that do not satisfy the criteria of the tributary area theory.

Limitations of the pressure arch theory

The pressure arch theory shares similar limitations with TAT, excluding the first two limitations. As it is a newly developed technique, the theory lacks credibility as it not been proven within the industry and thus should be used in conjunction with numerical modelling or previous stress values calculated to validate the load estimated. Also, it lacks a quantitative estimate of the pressure arch profile, thus difficult to estimate the intradosal pressure arch extent around a pillar. It also assumes that the pressure arch is symmetric, which is unlikely, particularly if previous mining has occurred above or below the seam of interest.

Appendix B

8.1 Pillar load, Pillar strength and Stability criteria using both PAT and TAT (Xcel sheets)

8.1.1 Pillar load using PAT and TAT

8.1.2 Pillar strength, w/h ratio and FOS using PAT and TAT

8.1.3 Probability of Failure and Probability of Survival using PAT and TAT