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Effect of abutment angle on stress distribution under supercritical longwall panels

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ABSTRACT

Efficient and effective ground control design in underground coal mines requires a sound understanding of the stress environment in the surrounding rock strata. This is particularly the case in multiple-seam mining where the stress environment is very different from that encountered when mining in strata that has not previously been mined. This is because previous mining activity causes a redistribution of the ground stresses, leading to the concentration of vertical load in chain pillars. The extra overburden load carried by the chain pillars in longwall mines is related to a quantity identified as the "abutment angle". This study aims to present the effects of the abutment angle on the final *in situ* vertical stress in the rock strata underlying supercritical longwall panels. The magnitude and distribution of these vertical stresses provide valuable information when considering multiple seam mine layouts below existing longwall panels. Wilson's equations have been used for the stress distribution induced in the pillars and longwall goaf, to estimate the stress changes in the strata beneath the mined panel using a plane strain elastic model. Finite element analysis was used to predict the final stress in the underlying strata. The results show that larger abutment angles generate larger stresses in the underlying stratum. For a given ratio of interburden to overburden there is a linear relationship between the abutment angle and the maximum normalised vertical stress.
Keywords: longwall mining, multi-seam mining, in situ stresses, abutment angle

1 INTRODUCTION

Multi-seam longwall coal mining is considered to be the future means of extracting a large portion of the underground coal in Australia. Untouched areas of coal reserves are dwindling and therefore there is a need to extract coal from below or above previously mined seams. Technological advances over the last two decades have enabled longwall mining to supersede room and pillar mining in terms of both safety and production levels. However, little research has been conducted into multi-seam mining where more than one seam is mined using the longwall method.

The *in situ* stresses encountered when second and subsequent flat-lying coal seams are to be extracted in a multi-seam mining operation are not the same as for virgin conditions, that exist prior to mining. In the case of the first seam to be mined, the vertical stress is usually considered to be homogeneous across the mining area, and the three principal stresses are usually oriented such that one is vertical and the other two are horizontal. In the case of multi-seam mining, previous mining in seams above or below the current seam will have altered the original *in situ* stress field. Although a lot of research has been conducted to understand what governs multi-seam interactions (Peng and Chandra 1980; Hsiung and Peng 1987; Hsiung and Peng 1987; Ellenberger, Chase et al. 2003; Gale 2004) there is still a limited understanding of the stress fields in which multiple seam mining is conducted. Understanding the stresses around a longwall panel and its gateroads enables mining engineers to predict potential failures and therefore to design effective ground control measures.

2 THEORY

The method of extracting coal from a seam influences how the *in situ* stresses are redistributed in the surrounding strata. Longwall mining redistributes *in situ* stresses to a greater extent than room and pillar mining (Haycocks and Zhou 1990). The extraction of coal from the first seam redistributes both the vertical and horizontal stresses in the stratum. The new stress state after first seam extraction is important as it represents the initial stress state for any subsequent mining in other seams.

A theoretical hypothesis on the stress redistribution after a longwall panel has been mined was first presented by Whittaker (1974) (Figure 1). For a single longwall panel, this hypothesis shows that the abutment stress in the ribs dissipates to the original overburden stress with increasing distance from the rib-edge. The peak stress induced in the ribs is off-set from the rib-edge. The loading in the goaf (collapsed overburden) returns to a maximum vertical stress at a certain distance behind the longwall face, after the goaf material has undergone collapse and consolidation, i.e., hardening.

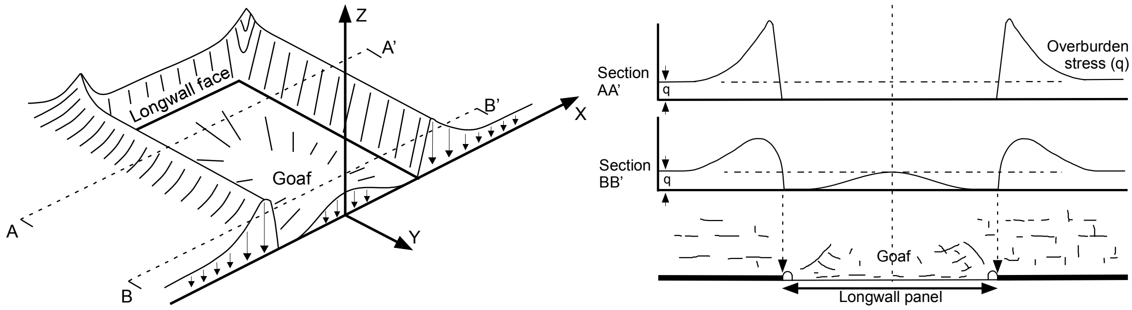


Figure 1. Strata pressure redistribution in the plane of the seam around a longwall face. Figure is based on the schematic diagram by Whittaker (1974)

2.1 Abutment angle

In order to accurately predict the stress distribution in a second coal seam that is to be mined below the first, it is necessary to understand how the total load of the system is re-distributed in the strata around the first mined seam. Therefore, it is important to be able to calculate the relative load above the longwall panel that is not carried by the goaf but is transferred to the pillars. This is referred to as the abutment load and it is typically calculated as the weight of a wedge of material defined by an abutment angle (β), also referred to as the shear angle. Usually, when longwall panels are wider than the overburden depth, the adjacent triangles formed by the abutment angle reach the surface (Figure 2) without intersecting. These are known as supercritical longwall panels where the full potential abutment loads are applied onto the adjacent pillars. The abutment load is denoted by A_s, and for supercritical longwall panels it can be calculated as:

$$A_s = qd = qH^2 tan\beta \qquad (1)$$

where q is the initial overburden stress at the seam level, d is the distance from the rib-edge to reach overburden stress in the goaf, and H is the depth below the surface to the seam being mined.

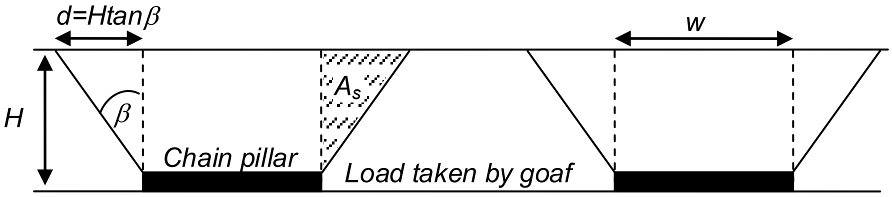


Figure 2. Redistribution of load onto chain pillars after mining of a supercritical longwall panel. Adapted from King and Whittaker (1971) and Wilson and Ashwin (1972).

The abutment angle is not considered to be a physical entity, but rather as a geometric variable that helps to easily quantify the overburden load above a goaf that is carried by adjacent pillars (Mark 1990; Colwell 1998). There is limited information on how to determine appropriate abutment angles. The reasons are two-fold: there is limited field data from which to calculate it; and there are many site specific values reported in the literature. Some studies have considered pillar stress measurements obtained from the field, and recommended the use of a single abutment angle for all longwall panel designs: such as 21 degrees in the USA (Mark 1990) and generally in Australia (Colwell 1998); 26 degrees for Central Colliery in NSW, Australia (Colwell 1998); and 10 degrees for the Southern coalfields in NSW, Australia (Colwell 1998). Others suggest that it is variable and may depend on the overburden depth (Heasley 2000) or the extracted seam thickness (Trueman 1990).

There is an alternative means of back-calculating the abutment angle, which involves using the estimated distance from the rib-edge to the point in the goaf where the stress has returned to the cover load. A large number of corresponding abutment angles have been proposed from estimated distances for the cover load to be reached from the rib-edge, viz., 0.3H to 0.4H which corresponds to β

values of 16.7 to 21.7 degrees (Whittaker 1974; Wilson 1983); and 0.12*H* which corresponds to a β value of 6.8 degrees (Smart and Haley 1987).

There is varied information about what the values of the abutment angle should be for longwall panels. As a result, this paper considers a range values of the abutment angle in order to assess its effect on the stresses induced in the underlying strata.

2.2 Vertical stress distribution in a chain pillar

There have been several theoretical models presented to describe the vertical stresses in chain pillars as a result of the removal of a series of longwall panels: Wilson (1972; 1983), Choi and McCain (1980), Hsiung and Peng (1985, 1986), and Mark (1990). A comprehensive review of each of these methods and their associated assumptions was presented in a paper by Mark (1990). The study by Mark (1990) also made comparisons of the predictions of each of these models with case histories in order to assess their robustness and make recommendations on appropriate input parameters. The comparison in the study showed that the models suggested by Wilson (1983) and Mark (1990) were rated to be the most flexible for any longwall design project, since they can consider a variable number of gateroads and mined seam heights. However, the equations of the Wilson model require a relatively large number of input parameters, which means they can be difficult to use for specific projects when there is limited information available. For the purpose of the present study, Wilson's analytical model provides equations that contain enough flexibility to consider many of the possible variables. These equations also have the advantage of ensuring that vertical equilibrium is maintained and so have been used.

Wilson's derivation acknowledges that the stress distribution would be different if only the seam yields (i.e., the coal pillar), in contrast to yield in the roof, seam and floor surrounding the pillar. In the case of seam only yielding (SO), the roof and floor strata are assumed to be much stronger than the coal material and therefore do not yield. For the case where yield occurs in the roof, seam and floor (RSF), it is assumed that the roof and floor rocks have a similar strength to the coal pillar. The primary difference between the two cases is that the depth of the yield zone (x_b) for the RSF is usually much larger, sometimes double that for the SO. For this paper, only the SO case was considered. Wilson's general stress distribution in a pillar consists of a yielded zone and an elastic zone in the pillar, for which the vertical stress equations are provided in Figure 3.

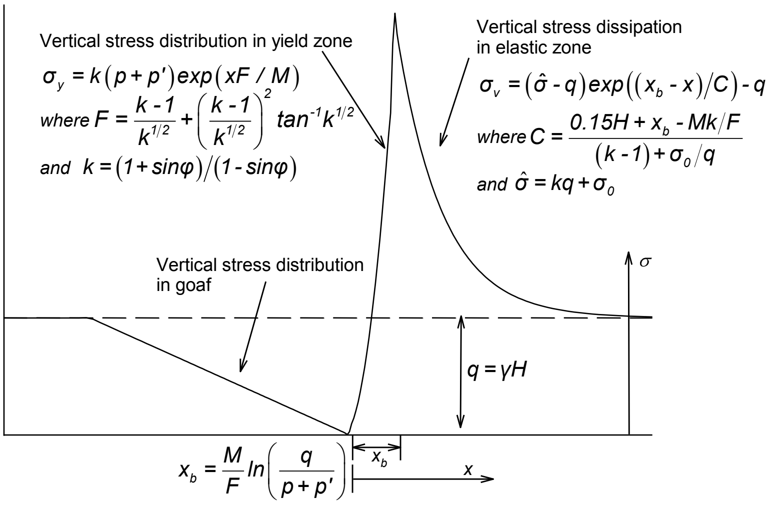
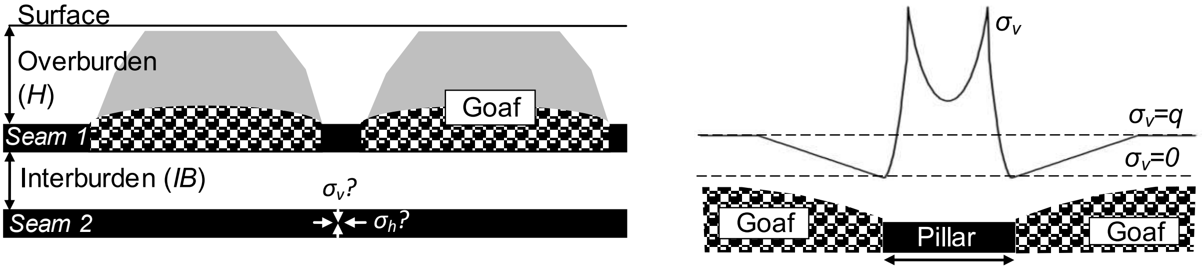


Figure 3. Wilson's (1983) equations for vertical stress in the vicinity of the rib-edge (x=0) of a longwall panel for conditions of yield in seam only.

3 APPROACH

The aim of this study was to identify the effect of the abutment angle on changes of *in situ* stresses in the strata underlying a longwall-mined seam, assuming the plane strain model shown in Figure 4(a). Only the case where the first seam has been extracted as a supercritical longwall panel has been considered here. Analysis of the problem has been simplified by only considering the areas where the vertical loading differs significantly from the magnitude of the initial overburden stress. This corresponds to the pillar region and some of the goaf, as shown schematically in Figure 4(b).



(a) (b)

Figure 4. Approach (a) whole model (b) area of focus, where q is equal to overburden stress.

For the cases studied here, it was assumed that the stress state in the ground is initially isotropic, i.e., at any location the vertical and horizontal stress components are equal prior to mining. The vertical stress distribution imposed on the underlying strata due to mining of the first seam were applied to a finite element model using Wilson's equations (Wilson 1983). Values of the variables used in these equations and the finite element modelling are presented in Table 1. It is also noted that, for simplicity, the effects of any shear stresses induced by mining of the first seam, at the interface between the coal pillar and the underlying strata (i.e., the top of the finite element model), have been specifically ignored. Any such effects are assumed to be secondary to those caused by the changes in vertical stress at this interface induced by extraction of the first longwall panel.

Table 1: Variable definition and values used in study

Variable	Definition	Values used in general case
γ	Unit weight	0.025 MN/m^3
H	Depth to top seam	150 m
M	Mined seam height	3 m
φ	Friction angle of coal	32 degrees
σ_0	Strength of coal at zero confinement	10 MPa
σ_0'	Strength of failed coal at zero confinement	0.25 MPa
p	Lateral restraint at the rib-edge	0 MPa
w	Pillar width	30 m

4 SOLUTION METHODS

The changes to the *in situ* stresses in seams underlying a seam being mined using the longwall technique were analysed using the displacement finite element software ABAQUS. Only the strata beneath the first seam mined were included in the spatial model. A plain strain rectangle with appropriate *in situ* stresses was meshed, and an elastic analysis conducted. The rectangular section of rock analysed was 300 m wide and 100 m high. Wilson's equations for the vertical stress changes corresponding to the first mined seam were applied to the top surface of the finite element model. Table 1 presents the input parameters considered in the model and adopted in Wilson's equations. The values for the general case are not intended to be indicative of any specific mine.

As discussed in Section 2.1, the abutment angle has been reported as ranging from approximately 10 to 30 degrees. Wilson's equations considered that the abutment angle was a constant of 16.7 degrees, such that the distance to return to cover load in the goaf was approximately 0.15 H. In terms of the abutment angle β, the distance for the vertical stress exerted by the goaf to return to the magnitude of the cover load corresponds to $\frac{1}{2}H\tan\beta$. This expression has been substituted into Wilson's equation for the constant *C* (Figure 3) thus providing a revised expression to calculate *C.*

5 RESULTS

Figure 5 presents the vertical stress distribution at the level of the first-mined coal seam for varying values of β, while still maintaining the values of all other variables as for the general case (Table 1). As expected, Wilson's equations indicate that larger abutment angles increase the total stress carried by the pillar, and as a consequence of maintaining equilibrium, there is an increase in the distance from the rib-edge required for the vertical stress in the goaf to return to the overburden stress.

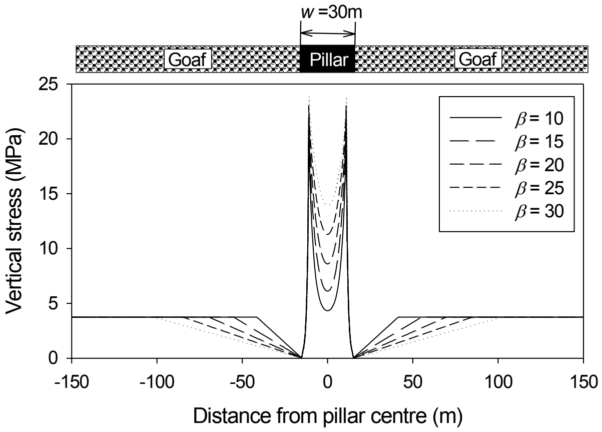
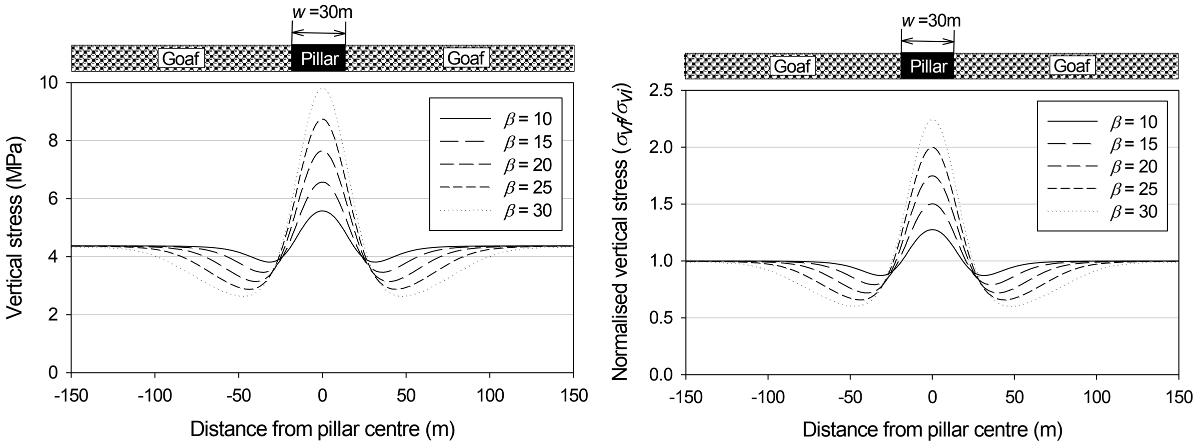


Figure 5. Vertical stress distribution at first-mined seam level calculated using Wilson's equation for yield in SO for a range of abutment angles.

The predicted stress distribution in the underlying strata predicted using Wilson's equation appears similar to that imposed by a rigid footing foundation (e.g., Poulos and Davis 1974). The key difference arises because Wilson's approach considers yielding in the coal seam, and thus the maximum vertical stress is finite and does not align with the rib-edge. Instead, the peak stresses occur at the boundary separating the yield and elastic zones within the pillar.

The vertical stresses induced in the underlying strata, as predicted by the finite element model for different abutment angles and for a value of *OB* / *IB* of 6, are shown in Figure 6(a). The overburden (*OB*), in an undermining environment, is the strata above the first mined seam, and the interburden (*IB*) is the strata between the first and second mined coal seam. For each of the abutment angles, these distributions exhibit the same shape and only vary in the relative magnitudes in both the horizontal and vertical directions. For ratio of *OB* / *IB* of 6, where OB = 150m, and β is 10 degrees, the maximum predicted vertical stress σ_{vf} is 5.58 MPa; when β is 30 degrees, σ_{vf} is 9.81 MPa. This difference of 4.23 MPa in predicted vertical stress change needs to be considered in light of the induced horizontal stress in order to assess the potential for adverse ground conditions.



(a) (b)

Figure 6. Vertical stress distribution below the first seam for OB / IB = 6 and a range of abutment angles: (a) final stress values, and (b) final vertical stress normalised by the initial vertical stress.

Figure 6(b) shows the predicted vertical stress after mining of the first seam (σ_{vf}) normalised by the initial vertical stress for the appropriate depth (σ_{vi}). For the abutment angle of 30 degrees, the predicted maximum vertical stress is 2.24 times the original *in situ* stress. Such a large variation in stress under an overlying pillar would require consideration of the available confining stress to assess the potential for adverse ground control conditions. This figure also shows that if the abutment angle is 10 degrees, the predicted maximum vertical stress is 1.27 times the original *in situ* stress. However, varying the abutment angle from 10 to 30 degrees increases the maximum vertical stress relative to the original stress from 1.27 to 2.24.

6 DISCUSSION

Predicted values of the maximum vertical stress, for a range of values of both the ratio *OB* / *IB* and the abutment angle, have been compiled in Figure 7. The maximum vertical stresses have been taken from the finite element vertical stress distributions for a range of abutment angles, such as presented in Figure 6(b), considering three different *OB / IB* ratios. These results show that the maximum vertical stress induced in the underlying strata is approximately linearly proportional to the abutment angle for a given ratio *OB / IB*. Therefore, overestimating an abutment angle will result in an over-prediction of the maximum stress induced in the underlying strata and in any lower seams to be mined.

The linear relationship between the angle β and the maximum normalised vertical stress is not the same for different *OB* / *IB* ratios. For smaller interburdens, i.e., large ratios of *OB* / *IB*, a deviation from the true abutment angle generates larger differences in the predicted stress than for deeper interburdens.

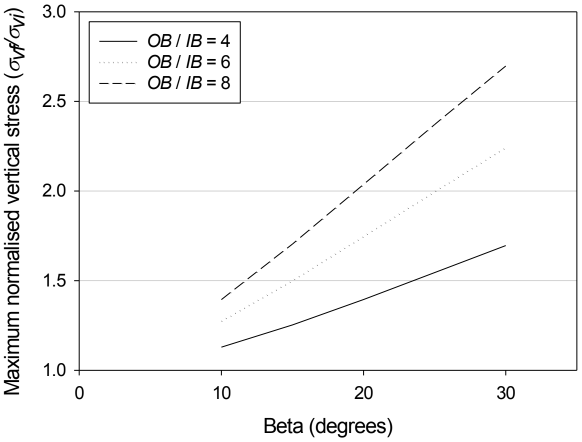


Figure 7. Maximum normalised vertical stress for a range of abutment angles and OB / IB ratios

7 CONCLUSION

This study has shown that larger abutment angles generate larger vertical stress in underlying strata. When the abutment angle was increased from 10 to 30 degrees, for an overburden depth of 150 m, pillar width of 30 m and *OB* / *IB* of 6, the maximum vertical stress increased from 1.3 to 2.2 times the original *in situ* stress. Larger errors in predicting the induced vertical stress can be expected for cases involving smaller interburdens if the abutment angle is inaccurately assessed. Hence the abutment angle significantly affects the vertical stresses induced in strata under supercritical longwall panels. The implications of these high vertical stresses need be considered to assess if adverse ground conditions might be experienced.

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