Stress analysis in failed roof at a longwall face

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ABSTRACT: This paper presents a conceptual work on roof failure mechanisms at a longwall coal mining face based on a multiple sliding block model. Underground observations of the caved roof strata at the longwall face indicate that many types of fracture exist and that two are dominant. In response to roof convergence close to the goaf, the stratified ground flexes resulting in shear failure along the weak bedding planes that are present in sedimentary strata, while sub-vertical fractures form just ahead of the longwall face in response to the mining induced stress state. These mining induced fractures usually occur at regular intervals during the mining face advance forming a typical blocky appearance within the roof strata. During roof movement interaction between the blocks occurs along the horizontal and near vertical fracture planes, this interaction can induce large stresses at the block boundaries at the roof level. Analytical and computational calculations attempt to interpret this movement and explain the stress distribution within the broken roof that results in high stress concentrations at the roof level. These stress concentrations can fail the already weakened roof strata leading to roof cavities that can seriously disrupt the longwall mining operation.
INTRODUCTION

The proposed strata interaction in the roof at the longwall mining face is based on earlier analysis of the floor failure at the longwall face (Nemcik, 2000). The roof failure conditions described are the result of the shear failure that occurs along the weak bedding planes within the sedimentary strata and sub-vertical fractures that normally form in response to changing stress abutments ahead of the longwall face. From rock mechanics principles it can be deduced that it is not possible to prevent the formation of mining induced fractures and roof convergence at the longwall face. Underground observations of the caved roof strata at the longwall face and numerical modelling of the longwall roof indicate that many types of fracture can occur however, only two types of fracture dominate roof failure; sub-vertical shear fractures and fractures caused by horizontal shear along the bedding planes. In response to roof convergence close to the goaf, the stratified ground flexes resulting in excessive shear stress along the weak bedding planes. Sub-vertical fractures form just ahead of the longwall face in response to the mining induced stress state. These mining induced fractures occur at regular intervals forming blocks during the face advance. The fractures that initially form ahead of the longwall face subsequently displace along the planes of failure when exposed above the longwall face. As the coal is mined below, stress relief initiates roof movement towards the goaf while roof convergence occurs towards the floor. The fractured roof blocks move in response to the roof displacement and in doing so interaction between the block sides occurs at the fractured surfaces. The analysis discussed here attempts to interpret this movement and explain how the stresses re-distribute within the broken roof during mining, leading to high stress concentrations at the roof level. Analytical formulation of this process has been developed and verified by numerical modelling and some of the results are presented here.

The analytical solution for multiple sliding blocks was specifically formulated to suit roof movement at the face where a number of possible block movements can exist. Continuous roof convergence creates sloping surfaces along the bedding planes on which the blocks can slide. Interacting at the boundaries the blocks experience shear and normal stresses along the fractured surfaces. One of these interactions was analysed to explain the stress distribution within the roof at the longwall face. The study assumes that there is a failed bedding plane at some distance above the roof level and that near vertical fractures form at regular intervals defining the geometry of the blocks. Progressive roof convergence during longwall mining and the reaction forces generated by the longwall supports are the primary driving forces to initiate the block movement. The analysis assumes planar bedding surface along which the blocks move. Analytical equations derived to calculate the magnitudes of stresses generated at the block boundaries can be used to estimate stress levels within the strain softened roof above the longwall face. These analysis also take into consideration the powered support loads that significantly contribute to the stress distribution within the softened roof strata.
2 POST FAILURE BEHAVIOUR OF STRATIFIED ROOF SPLIT BY MINING INDUCED FRACTURES

For simplicity the initial analysis assumes that a single bedding plane fails above the roof and that near vertical fractures develop ahead of the longwall face at regular intervals forming blocks, as shown in Figure 1. Longwall mining advance causes roof convergence within the face area which manifests as downward movement of the blocks along sub-vertical fractures, while slippage in the lateral direction occurs along the sheared bedding plane.

The behaviour of blocks varies according to the block geometry, angle of friction along the vertical fractures and the bedding plane that provide the contact for blocks to slip on. Even though the fracture surfaces are inclined at some angle to the vertical direction, vertical fractures were assumed to simplify calculation of forces within the blocks.
the frictional force at block sides \( Q \tan \phi_v \), where \( \phi_v \) is the angle of friction along the vertical fractures;

- the powered support load \( P \);

- the reaction force at the top of each block consisting of the normal force \( N \) and the shear force \( N \tan \phi_h \), where \( \phi_h \) is the angle of friction along the horizontal bedding;

- an angle of deflection \( \alpha \) of the roof from the horizontal.

Note that the blocks move continuously downwards and towards the goaf and the shear forces experienced along the sides of the blocks are in the response to block movement. The normal force \( N \) at the top of each block is contributed to by the powered support loads and the friction along the vertical fractures during the increase in roof convergence. The ability to slip either along the vertical plane or along the horizontal bedding appears to be related to the roof shape, block geometry and the angle of friction along the slip surfaces.

![Figure 2. Schematic representation of block movement in the roof.](image)

Three possible cases of block movement were identified and each case is illustrated in Figure 4. Case 1 assumes that as the roof deflects due to convergence, block rotation does not occur and that the roof deflects linearly at an angle, \( \alpha \), from the horizontal. Case 2 assumes that the blocks rotate during displacement, but the roof still deflects linearly, while case 3 assumes block rotation and curvilinear roof deflection. In this paper the only case 1 is analysed.
3.1 Slip Along all Fracture Boundaries, No Block Rotation

This model assumes that movement occurs along both the vertical and horizontal fractures simultaneously. A free body diagram of a single block was presented in Figure 3. The angle of friction $\phi$ along the failed bedding plane will depend on the mechanical properties of the geological discontinuity along which the failure is developed. For the blocks to slip along the failed bedding plane, the force $F_s$
overcoming the shear resistance, $S'$, must exceed the Mohr-Coulomb criterion:

$$F_s > S_h \quad \text{and} \quad S_h = N_j \tan \phi_h$$

where:

- $F_s$ = shear force on the bedding plane
- $S_h$ = shear resistance along the failed horizontal bedding plane
- $N_j$ = normal force to the bedding plane
- $\phi_h$ = angle of friction along the failed horizontal bedding

Using the information from the free body diagram in Figure 3 it can be shown that for planar bedding the lateral interaction force, $Q$, can be calculated using equation (1) below. In this case the maximum lateral force, $Q_{n'}$, concentrated at the point of contact near the bottom corner of any block, $b_n$, can be calculated as follows:

$$Q_{n'} = \sum_{i=1}^{n} (P_i - W_j) \cos \alpha$$

$$h_i = \frac{L \left( \frac{P-W}{2} \right) (\sin \alpha + \cos \alpha \tan \phi_h)^{i-1} - (\sin \alpha + \cos \alpha \tan \phi_h)}{(P-W) \cos \alpha + L_i (1 + 2 + 3 + ...) \tan \phi_h}$$

Equation 3 indicates that as the distance of a block from the face decreases, the vertical distance from the bedding plane of the centroid increases until it coincides with the bottom corner of the block, where $h_i = h_P$. Equation (3) also indicates that $h_i$ is sensitive to the angle of friction along the vertical fractures.

### 3.2 Calculations of Lateral Forces in the Roof Using the Derived Equations

Assuming the displacement conditions of case 1, as described previously, the derived equations were used to calculate the lateral forces that develop within the stratified roof at the longwall face for a geometry where the roof blocks were 2m high and 1m wide. This geometry assumes that a single bedding plane located 2m above the roof level fails in shear and that vertical fractures develop each time a 1m wide coal slice
is cut at the longwall face. Under normal loading conditions the powered support exerts large roof loads at the canopy rear and lower loads at the tip, however, in this case an average support load of 100 tonnes per metre along the canopy length was applied at the face of each block. The results are presented in Figure 5.

3.3 Determination of Stress Distribution in the Roof Using a Numerical Model

A 2-dimensional model of case 1 was developed using FLAC (Itasca, 2005). The lateral stress contour pattern shown in Figure 6 indicates very similar results to those calculated using the derived equations. The FLAC model showed that the condition when the blocks do not rotate applies only to a limited case where the angle of friction along the vertical fractures is relatively low and the friction along the bedding plane is at least 25°. The calculated and modelled results are shown together in Figure 7, however direct comparison can only be made within the region circled in yellow, where no block rotation is likely to occur. An analytical solution incorporating the block rotation is required to calculate the Q forces among the blocks to enable more accurate comparison with the FLAC model.

![Figure 5](image_url)

Figure 5. Calculated lateral forces in the roof above the longwall face for linearly increasing roof convergence.
Figure 6. Example of a numerical model showing contours of lateral stress during block movement.

Figure 7. Calculated and modelled lateral forces in the roof above the longwall face for linearly increasing roof convergence.
From the free body diagram shown in Figure 3 the condition for block rotation was evaluated and is shown below:

\[ Q_{i+1} \left( \frac{H_i}{2} \right) + N_i \cos \alpha H > (Q_{i+1} + Q_i) \left( \frac{L}{2} \right) \tan \beta + N_i \cos \alpha L + Q_i \left( \frac{h_i - H}{2} \right) \]

If the left hand side of the equation (4) is less than the right hand side, the block will rotate to the position where the block base will be in full contact with the bedding plane. Equation (4) indicates that if the angle of friction along the bedding plane decreases while the friction angle along the vertical fractures increases, the chance of block rotation will increase. This was also observed in the FLAC model and is indicated in Figure 7. Reduction of the geometrical ratio \( H/L \) would also increase the likelihood of block rotation. On the whole, the modelled \( Q \) forces in the roof indicate that in most cases there was no significant difference between block rotation and no rotation.

The data indicate that the lateral loads increase for higher coefficient of friction along both the vertical fractures and the horizontal bedding plane. Under normal conditions the angle of friction along the sub-vertical fractures would typically exceed 30° while the angle of friction along the failed bedding plane can vary ranging from low values for saturated claystone or mudstone to about 35° for sandstone. The calculations indicate that the magnitude of the lateral forces that develop at the roof surface close to the longwall face can exceed 600 to 1000 tonnes per metre of the longwall face length. The area at which the blocks interact is usually very small and can become a point load during block rotation. If that is the case then compressive rock failure at the roof level would be highly probable even at moderate lateral force levels.

### 3.4 Stability of the Longwall Face

For roof stability at the longwall face the fractured roof must remain under slight compression to arrest movement along the fractures that may lead to excessive convergence and loss of roof integrity. Success of the strata control in the area of the unsupported roof section (ahead of the canopy) is related to the balance between the total stress relief and excessive compression. The powered supports used at the longwall face do not provide the necessary support to the roof at or ahead of the canopy tip directly and an alternative stress source is needed to confine the fractured roof strata. The equations describing the block movement indicate that the longwall support loads provide this support indirectly by imparting lateral load at the roof level, thus confining the fractured roof strata.

### 4 CONCLUSION

The purpose of this paper was to stimulate further research in the topic to prove that it is possible to analyse and understand stress paths that occur within the softened ground. Even though the numerical modelling is the preferred option to analyse various stress regimes that may occur at the longwall face, numerical modelling
is only as good as the level of understanding of the ground behaviour. Current numerical modelling techniques have problems with determining ground fracture mechanisms as to how and where they occur, in what direction they propagate and how far they travel. The analytical derivations presented here may provide the reader with a better understanding of the ground behaviour at the longwall mining face and indicate the limitations of numerical modelling techniques.

Further work needs to be conducted in this field to improve understanding of the fractured ground behaviour and develop numerical modelling techniques to simulate fracture formation and propagation within the stratified ground at the longwall coal mining face.

5 REFERENCES
