A METHODOLOGY FOR DETERMINING GOB PERMEABILITY DISTRIBUTIONS AND ITS APPLICATION TO RESERVOIR MODELING OF COAL MINE LONGWALLS

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Abstract

Methane can be a significant hazard in coal mine longwalling operations and extensive methane mitigation techniques are employed by coal mine operators. Reservoir modeling techniques are used to better understand the liberation and migration of methane from the surrounding rocks towards the mine ventilation system. The caved rock behind the advancing longwall face, known as the gob, can contain high void ratios, providing high permeability flow paths to the methane. The gob is progressively compacted by the weight of the overburden, resulting in a reduction in the void ratio and associated permeability. Estimating the permeability distribution within the gob poses challenges due to its complexity. The authors have developed a new methodology to determine both horizontal and vertical variations in the permeability of the gob. Variations of the permeability in the vertical direction are based on a model of caving and block rotation, which considers the effect of block dimensions and fall height on the void ratio. Gob compaction by the overburden and associated permeability changes are determined from a three-dimensional geo-mechanical model which simulates the gob as a strain hardening granular material. The resulting three-dimensional permeability distribution in the gob is then transferred to a reservoir model. The paper demonstrates the application of the method and shows that reasonable results are obtained when compared to empirical experience and measurements.

Introduction

Underground longwall mining of coal causes large scale disturbances of the surrounding rock mass such as changes in the ground stress and fracturing of the rock. These changes increase the permeability of the rock mass and can liberate methane from the surrounding strata. Methane can be a significant hazard in longwalling operations and extensive methane mitigation techniques are employed by coal mine operators. These can include pre-drainage of methane ahead of the advancing longwall face by horizontal drainage holes and methane extraction by vertical holes drilled from surface, known as gob vent boreholes.

The caved rock behind the advancing longwall face, known as the gob, has a significant effect on methane flow patterns. The gob can contain high void ratios, providing high permeability flow paths that can provide flow paths from the working face to the methane liberated from the disturbed strata. As mining progresses, the gob is gradually compacted by the weight of the overburden, resulting in a reduction in the void ratio and associated permeability.

The complex processes of methane liberation, flow through fractures and migration towards the operating longwall face are being investigated at the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory, through combined geomechanical and reservoir modeling. A geomechanical model is used to characterize the stress changes and rock fracturing that accompanies the advancing longwall face, as well as gob formation and compaction behind the face. Output of the geomechanical model is used to develop permeability distributions in the rock mass around the longwall panel for input into the reservoir model, as described in Esterhuizen and Karacan (2005). The accuracy of the models in predicting methane flow in the vicinity of the longwall face is dependent on an accurate representation of the gob permeability distribution.

This paper describes a methodology for calculating permeability variations in the gob suitable for reservoir modeling or other flow models. The method considers both horizontal and vertical variations of the void ratio during gob formation and subsequent compaction. The permeability distribution is calculated using equations for flow through granular materials. The resulting three-dimensional permeability distribution in the gob were transferred to a reservoir model of a typical longwall panel in the Pittsburgh Coalbed. The leakage flow into the gob, methane distribution within and effects of gob vent boreholes on flow patterns are simulated.

Computational fluid dynamics (CFD) models have been utilized before for gob (caved zone) modeling (Balusu et al., 1996; Yuan et al., 2006). However, to the best of our knowledge, a detailed caved zone model investigating the flow in the mine and gob areas has never been developed using a reservoir modeling approach.

Gob Characteristics

The gob is formed by rock fragments that fall from the roof strata into the void created by the removal of the coal bed. The bulking of the gob is affected by the fall height of the rock fragments as well as the size and shape of the fragments. When the fall height is larger than the lateral dimension of the rock fragments, they are more likely to rotate and come to rest in a jumble, which produces relatively large void spaces, shown in Figure 1(a). This is known as fully caved rock. As caving proceeds upwards, the caved rock occupies an ever increasing proportion of the free space, thus reducing the fall height of the subsequent fragments. As the fall height reduces, the potential for fragments to rotate diminishes and the amount of bulking is reduced, shown in Figure 1(b). This is known as partially caved rock.

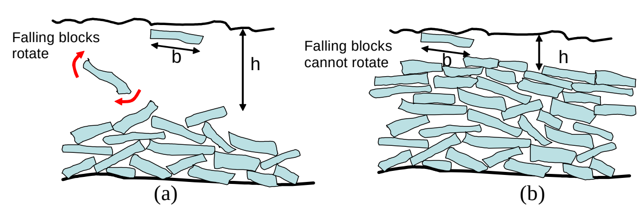

Figure 1. Effect of fall height on void space between gob fragments. Voids between fragments are large when the fall height (h) is large relative to block width (b). Voids reduce as the fall height reduces and rotation is inhibited.

The variation of the bulking of the gob in the vertical direction was estimated using a procedure suggested by Munson and Benzley (1980). The procedure assumes that maximum bulking of the caved rock will occur when the fall height exceeds about twice the block width. The maximum bulking factor was assumed to be 75%, after tests on simulated gob materials (Pappas and Mark, 1993). The bulking factor (S) is expressed as:

$$S = \frac{V_r + V_v}{V_r}$$

V_r is the rock volume and V_v is the void volume. It was further assumed that a smooth transition will occur from the maximum bulking factor to zero when the fall height is zero. Figure 2 shows the relationship between the ratio of fall height to block width (h:b) and bulking factor used in this paper.

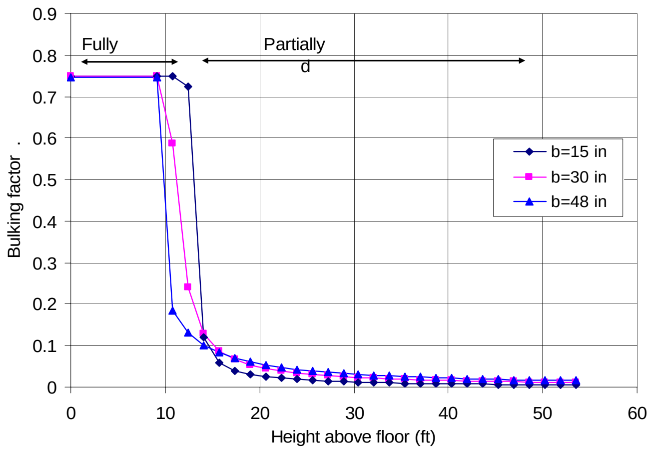

Figure 2. Calculated variation of the gob bulking factor above the coal bed floor for a mining height of 6ft and various block widths (b). The fully caved and partially caved zones are indicated.

The resulting variation in the bulking factor with vertical distance above the floor of a 6ft high coal bed was calculated using this relationship for various block widths. The results are shown in Figure 3. It can be seen that near the floor of the mined coal bed, the bulking factor remains at about 75%, but there is a rapid drop in the bulking factor at about 9ft to 15ft above the floor, depending on the block width. This lower zone is known as the fully caved zone and the upper is the partially caved zone. The results show that the overall variation of the bulking factor is not particularly sensitive to the selected block width.

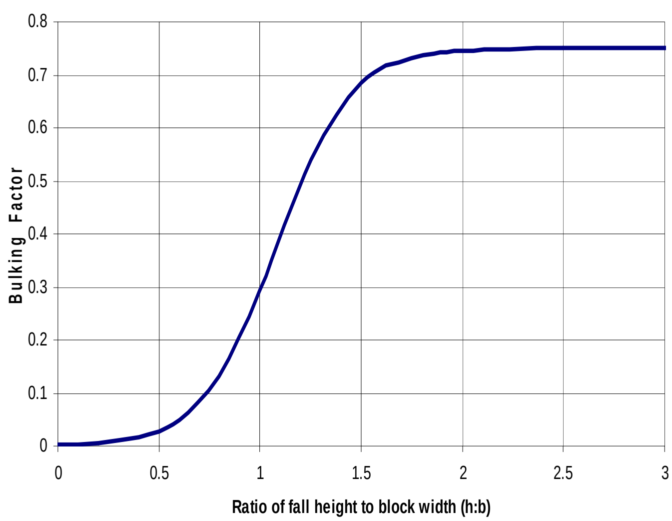

Figure 3. Relationship between bulking factor and ratio of fall height to block width of caved fragments.

The effect of gob compaction by the weight of the overlying strata was introduced by assuming the bulking factor will reduce in direct proportion to the amount of compaction. For example, 10% compaction will reduce the bulking factor by 10% of the current value at all points, regardless of the distance above the coal bed floor. This is a simplifying assumption, which does not significantly affect the permeability results. Further work is planned in which variable compaction will be considered.

Permeability Calculation

The Carman-Kozeny equation for flow through porous media was used to estimate the permeability of the gob (K) as follows:

$$K = \frac{K_0}{0.241}\left(\frac{n^3}{(1-n)^2}\right)$$

Where K_o is the base permeability of the broken rock at the maximum porosity, and n is the porosity. The value of K_o was taken as 1x10^6 md which places it the "open jointed rock" range according to Hoek and Bray (1981). This permeability value also falls within the same range of permeabilities calculated from experimental friction factors for flow through crushed stone, compiled by Stephenson (1979). The K_o value of 1x10^6 results in realistic gob gas venthole production when used in reservoir modeling of longwalls (Karacan et al., 2006). Using the above equation, the calculated permeability variation in the gob is shown in Figure 4 for various block widths.

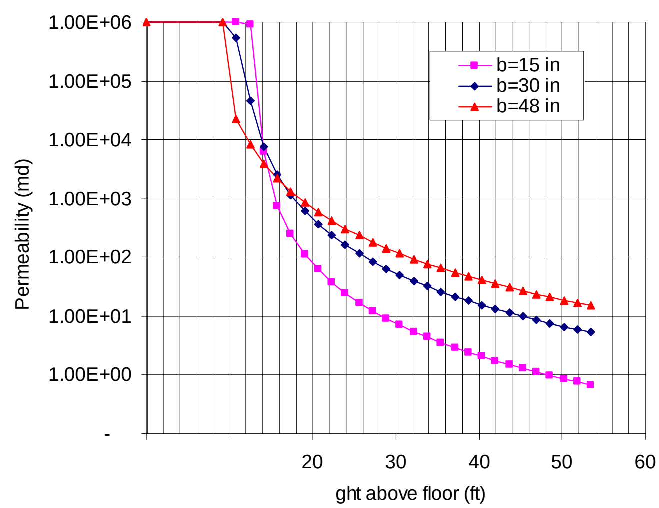

Figure 4. Variation of permeability in the gob above the coalbed floor for a mining height of 6 ft.

The results show that the permeability is 1x10^6 md in the lower part of the gob, where bulking is at the maximum, as specified in the assumptions. This high permeability zone extends about 1.5 times the mining height. The permeability rapidly decreases at points that are more than about 10ft above floor. The permeability soon drops to 100 md at a height of about 20 to 30 ft, which places it the permeability range of jointed rock. This height corresponds with the empirical observation that cave rock extends about 4 to 6 times the height of the mined coal bed (Mucho et al., 2000).

Distribution of GOB Permeability in a Mined Panel

The compaction of the gob behind the advancing longwall face and the associated permeability changes are determined through the use of the FLAC3D numerical modeling program (Itasca, 2005). The program allows realistic modeling of stress redistribution about a longwall panel and is able to model rock fracture and gob compaction. The gob is modeled using the double yield material type in FLAC3D, which represents materials in which there may be significant irreversible compaction in addition to shear yielding. The material parameters were selected to simulate a gob material that has an initial bulking factor of 0.75, displaying an exponential increase in load as it is compacted by the weight of the overlying strata. Figure 5 shows the relationship between gob stress and compaction used in the models. Further details of the modeling approach and typical input parameters are presented in Esterhuizen and Karacan (2005).

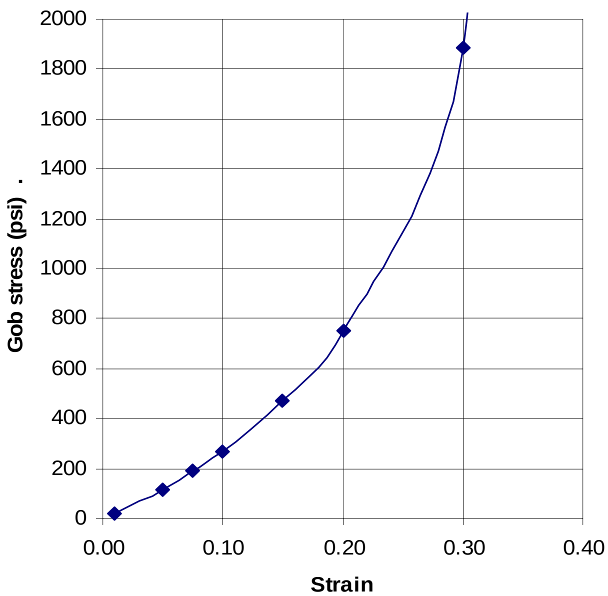

Figure 5. Relationship between gob strain and stress used in the FLAC3D numerical model.

The FLAC3D model can be set up to simulate the progressive extraction of coal by an advancing longwall panel. The void behind the face and the roof rocks up to 4 or 6 times the mining height is filled with gob material. The overburden rocks in the model will subside and compact the gob until a state of equilibrium is reached. The compaction of the gob is obtained by querying the FLAC3D model at selected points. Knowing the compaction distribution, it is possible to calculate the remaining void space at each point. It is then a simple matter to calculate the porosity and associated permeability values using the Carman-Kozeny equation. It was assumed that the horizontal permeability is twice the vertical permeability, owing to the shape of rock fragments.

A simple algorithm was written using the internal programming language in FLAC3D to write a text file with x,y,z coordinates, porosity and permeability values in an appropriate format for import into the reservoir model. Figure 6 shows the resulting distribution of permeability in a horizontal slice taken 3 ft above the floor of the coalbed, as determined for a longwall panel at a depth of 600 ft. It can be seen that permeability varies considerably within the gob. Near the edges of the gob, the permeability is relatively high, with a maximum of $1x10^6$ md near the corners of the mined panel. The permeability in the central part of the gob is relatively constant at about $1x10^5$ md.

GOB Representation in Reservoir Model

Model and gob geometry

A reservoir model was created based on the characteristics of a typical Eastern U.S. longwall mine operating in the Pittsburgh Coalbed. The model was created using the GEM (General Equation of State Model) reservoir simulator (Computer Modeling Group, 2003). In building the model, the geology above the Pittsburgh Coalbed that would form the caved zone after mining was considered. The thickness of the caved zone in this area is estimated to be 4-6 times the thickness of the mined height (Mucho et al., 2000). Within that zone, thin sandstone-shale sequences, limestone and Redstone Coalbed are the major layers. Their representative reservoir properties were assigned the same as reported in earlier publications (Esterhuizen and Karacan, 2005; Karacan et al., 2006).

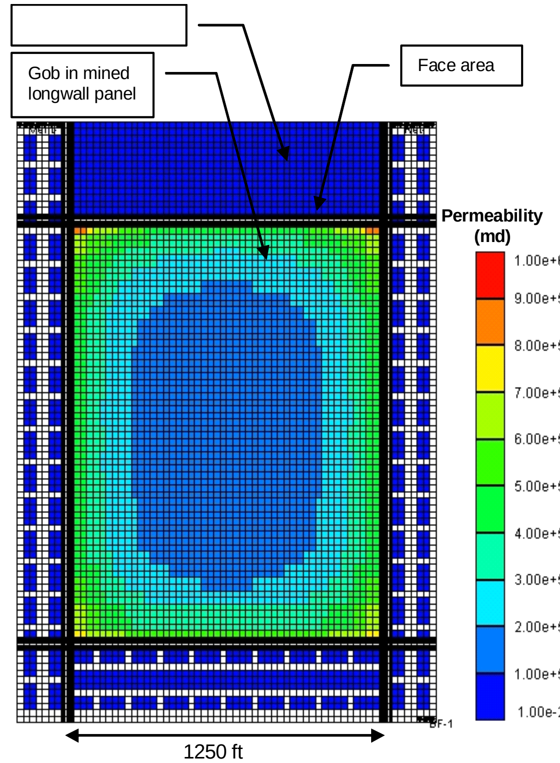

Figure 6. Plan view of a longwall panel showing the distribution of permeability in the fully caved gob as determined from the results of FLAC3D modeling.

The model dimensions were based on the width of a typical longwall panel, the surrounding entries and the thickness of the expected caved zone. According to this, the width of the model was 1,650 ft, 1,250 ft of which was due to the panel width and 200 ft on each side of the panel, for the gate entries. The height was 35 ft, based on the expected thickness of the caved zone. Thus, the gob in this study represents only the fully and partially caved zone. The dimensions of the entries and pillars were based on representative dimensions from mine maps. The tailgate and headgate consisted of three entries each, spaced 100 ft apart. The length of the model was 2,300 ft.

In the development of the reservoir model, non-uniform grids and local grid refinement were used in order to be able to create the rock layers and the details of the mining environment. In the model, 12 layers ranging 1-6 ft in thickness represented the rock layers immediately above the Pittsburgh Coalbed (bottom-most layer). Figure 7 shows the 3-D grid model. The layers above the mining layer were cropped in order to better visualize the details. A face area (15 ft in width) was created between the unmined coalbed and the gob to represent the working face and enable face ventilation.

Coal, gob and rock properties

Due to the nature of the environment represented, the model includes three different reservoir sections for modeling purposes:

The first section includes the "undisturbed" rock units outside the gob, which consist of the unmined coalbed and the rock layers above the coalbed. The initial, pre-mining reservoir properties to the coal and non-coal units were based on data given in earlier publications (Esterhuizen and Karacan, 2005; Karacan et al., 2006).

The second, and most important section, is the inner part of the model representing the gob. Changes in flow and fluid storage-related properties (mainly permeability and porosity) were imported directly into the reservoir simulator to specific grid addresses from the FLAC3D results by the techniques described in previous sections of this paper.

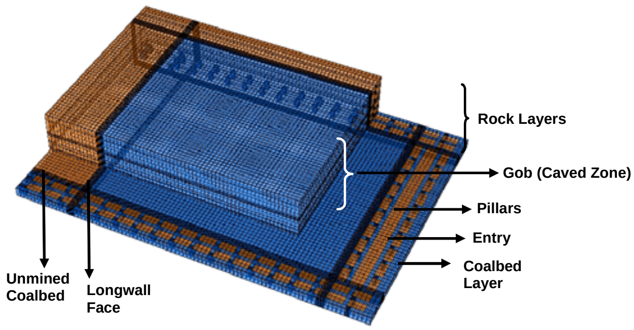

Figure 7. A three dimensional grid model of the gob and the mining layer. The top layers were cropped to visualize the modeled mining layer.

The third section comprises of the entries and longwall face in the mining layer. Since these are high permeability, low resistance and high porosity areas, the property assignments were made to reflect those characteristics. In the model, the entries surrounding the longwall panels serve as main pathways for ventilation airflow. Thus, the permeability for this portion of the mining layer were assigned an average high value [10^{-7} m^2 (10^8 md)] within the allowed limits of the simulator for minimum resistance. A fracture porosity of 99%, on the other hand, was designated to these areas. Since matrix-to-fracture mass transfer is not important in these areas, the matrix was assigned null properties.

Ventilation scheme and ventilation controls

Ventilation is one of the most important elements of underground longwall mining to dilute and render harmless toxic or explosive gas and dust in the mine. In the Northern Appalachian Basin, the longwall mines operate with a bleeder ventilation system. This scheme ventilates the entries, face and gob through leakage and carries away the contaminated air along return entries and the bleeder. A typical bleeder ventilation scheme was modeled in the mining layer to simulate those effects. The flow rates and pressure differentials were created using injection and producer wells to represent intakes, returns and the bleeder fan, which dictate the ventilation pressures as well as the direction of the flow in the model. Auxiliary ventilation structures such as curtains, stoppings and regulators were also modeled to divert or stop the flow and to control the pressures, shown in Figure 8.

Ventilation air intakes 1 and 2 (I_1 and I_2) shown on the headgate side (Figure 8) were represented by injection wells providing air into the entries with 15 psi pressure and 30,000 and 50,000 cfm air flow rate, respectively. The injection wells also controlled the intake ventilation pressure in the entries. Some of the intake flow admitted into the headgate entries is diverted into the face area using ventilation curtains. The curtains were represented by permeable grids that had higher resistance compared to the entries themselves. A small portion of the face air was also diverted to the conveyor belt entry before it enters the face area. This was achieved utilizing a producer well operating at atmospheric bottom-hole conditions to create a pressure sink.

The amount of air leaving the face was removed by returns (R_1 and R_2) which were modeled as vertical producer wells operating 14.5 bottom hole pressure. The bleeder fan was similarly modeled with a bottom-hole-pressure of 12.5 psi. The air flowing in the headgate entries was wrapped around the gob by the influence of the bleeder fan. Regulators, represented by higher resistance grids, were also employed at the usual locations to control the flow around the gob area.

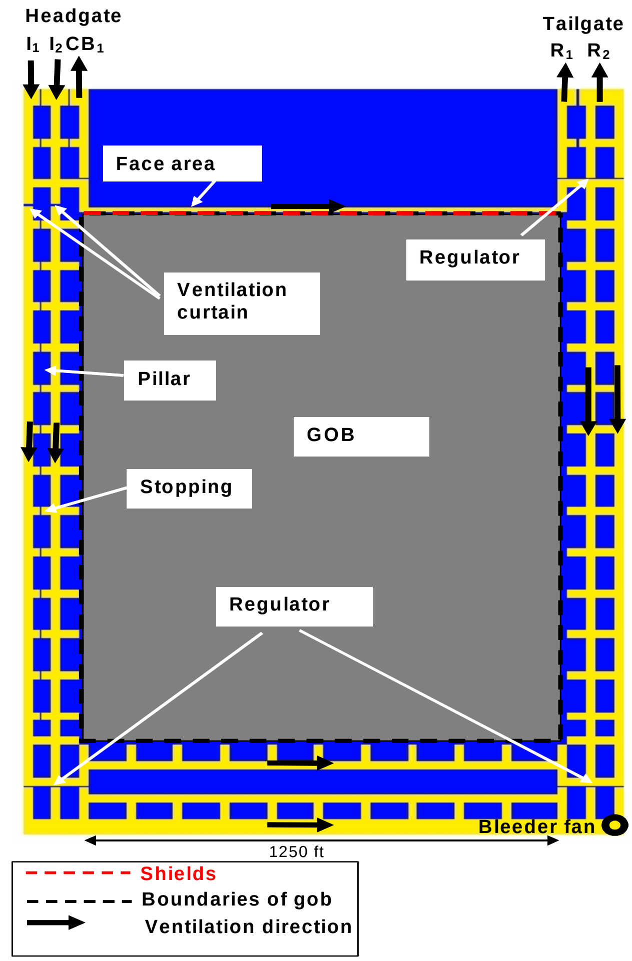

Figure 8. Mining layer in the model that shows the ventilation paths, elements of ventilation system and various modeled features.

It is known that air leakage from the face area to the gob is resisted by the shield supports. The shields were modeled by decreasing the transmissibility of the first layer of gob grids in the direction perpendicular to the face by 50%, an estimated value in the absence of in-mine measurements of this resistance. It was not possible to model the presence of each shield individually. Therefore, the total number of grids were divided into groups so that every 5 shields were represented in one grid for this purpose.

Applications of Reservoir Model-Example Results

The developed reservoir model was used to investigate flow in the caved zone section of the gob and to compare the results to empirical experience and field measurements.

Air leakage into gob

Air leakage into the caved zone in longwall operations affects the efficiency of the ventilation system. In gassy mines, air leakage may be used as a means of ventilating the gob so that the methane being released in the caved zone close to the face line will not enter to the working area (Brunner, 1985). Also, in longwall mines, the velocity of air leaking into the gob is important to control spontaneous combustion. The availability of air and its velocity may affect oxidation of coal in the caved zone. Thus, it is important to evaluate and quantify the leakage pattern and quantities. Numerical models, CFD or reservoir, may help understanding and controlling leakage into the caved zone.

The reservoir model was used to analyze the air flow within the caved zone imposed by the ventilation pressures in the entries. Figure 9 shows the flow patterns within the gob close to the face. The arrows indicate the direction of flow without any magnitude. The arrows indicate that most of the leakage into the gob occurs around the headgate entry where the flow is forced into work area. Some of the flow is distributed within the gob, and some migrates along the face line behind the shields and then converges into the return entries at the split point in tailgate.

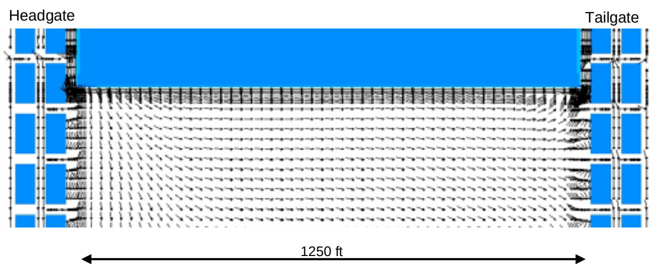

Figure 9. The air flow lines within the caved zone in the vicinity of the face area.

Figure 10 shows the cross-directional velocity contours within the caved zone. The highest velocities, in the face and entries, were eliminated from the map in order to better visualize the flow in the gob. The contour map shows that the highest velocities occur behind the shields where the caved zone is rather loose and permeable. The velocities in this region are 60-80 ft/min and converge towards the return at the end of the shields. In deeper regions behind the shields, both the flow broadens and starts to flow towards the tailgate entries and attenuates in velocity. A higher-velocity leakage zone is observed at the back of the panel along barrier pillars also, where the values may reach 40-50 ft/min.

Previous studies performed to investigate the leakage flow into gob revealed flow paths similar to those reported in this study. Michaylov and Vlasseva (1995) showed that velocities are higher alongside the porous and permeable sections of the gob. They have calculated that the velocities behind the shields can be around 30 ft/min. They have also calculated increased velocities at the back of the panel as observed in this study. The differences in calculated velocities between the two studies may be due to differences in the imposed boundary conditions and how the gob is modeled.

The contours of the x-component of the velocity of the air entering to the tailgate cross cuts (Figure 10) show that the velocity decreases from a maximum value in the cross cut in the immediate vicinity of the face line to a minimum close to back of the panel. The value ranges from 50-90 ft/min to 0-10 ft/min based on the location of the cross cut along side the gob. The measured data presented by Brunner (1985) shows a similar behavior for the change of magnitude of the air flow path. The velocity is highest in the first cross cut outby the face line and lowest in the cross cut closest to the back of the panel. The measured data, reported as volumetric rate, shows that the maximum flow velocity is around 30-40 ft/min and the mini mum is around 0-10 ft/min.

Effect of introducing a gob gas venthole

In the Eastern U.S., gob gas ventholes ideally are drilled to within 40 or 45ft of the top of the coalbed (into the fractured zone, but not into the caved zone) and are completed with 7-in casing and 200ft of slotted pipe on the bottom. Usually, a vacuum is applied to these ventholes by installing exhausters on the surface well head. The purpose of this completion strategy is to create a pressure sink across several potential gas-bearing horizons and to capture the released gas before it can enter the underground workplace. For these gob gas ventholes to work effectively, they must be drilled close enough to the mine to capture methane from the fractured zone but far enough above the caved zone to minimize the amount of ventilation air that is drawn into the ventholes. However, sometimes gob gas boreholes are inadvertently drilled into the caved zone. This results in the production of excessive mine air from the gob gas venthole and decreases its effectiveness (Karacan et al., 2005 and 2006).

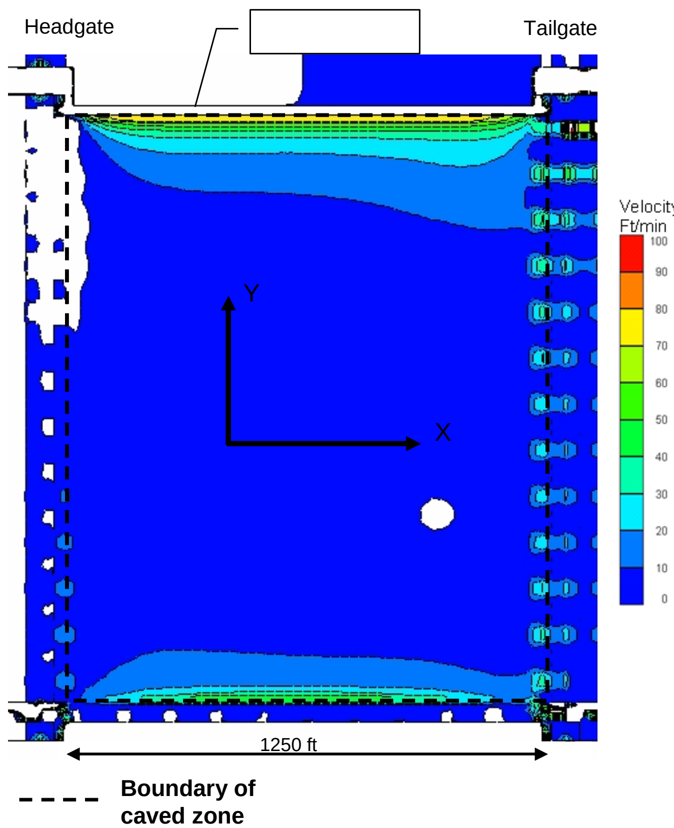

Figure 10. Contours of the x-component of the velocity in the fully caved zone of the gob.

The influence of a gob gas venthole accidentally drilled into the caved zone was investigated using the reservoir model. For this purpose, a gob gas venthole was placed on the tailgate side of the panel (Figure 11). It has been modeled as 7-inch-diameter and operated with 2 psi of suction, to simulate the exhauster. However, it was modeled as drilled half way into the caved zone, to the boundary between fully caved and partially caved zones in the gob.

Figure 11-A shows the disturbance in the air flow lines created by an over-drilled gob gas venthole in the fully caved zone of the gob. The flow lines show that the gob gas venthole attracts the air towards its drainage area, although it does not penetrate that deep. Of course, this situation both impedes the ventilation of the caved zone and reduces the ventilation system efficiency. Figure 11B presents the impact of the gob gas venthole on a vertical cross section across the venthole and shows that, besides draining gob gas in horizontal direction, it produces excessive amounts of air from the lower levels of the caved zone. This observation is substantiated by the field measurements of methane production from gob gas ventholes unintentionally drilled too deep into the caved zone, presented in Karacan et al. (2006). The methane concentration measurement from such a venthole showed that the methane concentrations are 30-40% lower than its counterparts drilled above the caved zone (Figure 10).

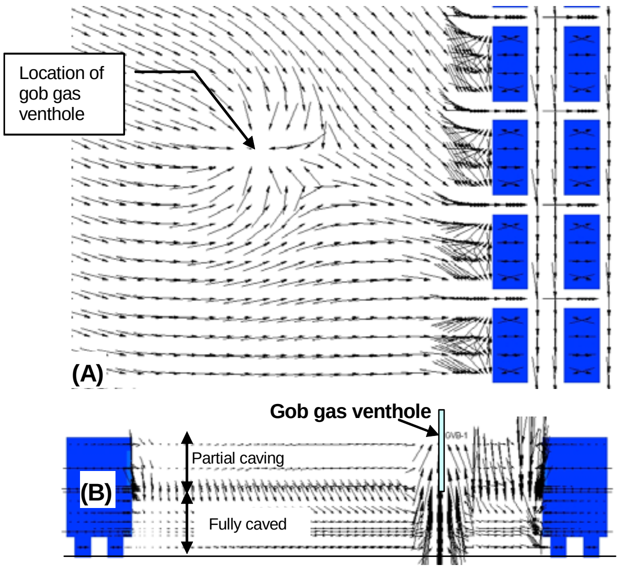

Figure 11. Influence of a gob venthole penetrating to the caved zone. (A) A plan view of the lower part of the caved zone near tailgate entries and (B) A vertical cross section through the gob gas venthole location.

Discussion and Conclusion

The paper presents a new methodology for calculating permeability variations within the gob of a coal mine longwall panel. The method accounts for permeability variations in the vertical direction as the bulking factor changes as well as the lateral direction as the gob is compacted by the weight of the overburden.

The results show that gob permeability is a maximum in the fully caved, lower part of the gob. The fully caved zone extends to about 1.5 times the mining height.

The permeability rapidly drops by several orders of magnitude in the partially caved zone which is located above the fully caved zone. The permeability in this zone drops to that of fractured rock at a height of about 4 to 6 times the mining height. This is consistent with empirical observations of the height of caving.

Gob compaction by the weight of the overburden rocks is shown to cause further lateral variations of permeability of about one order of magnitude.

Application of the methodology to a reservoir model of the gob and surrounding entries in a longwall operation shows that realistic results of flow within the gob and surrounding excavations are obtained.

A model investigating leakage flow in the gob behind the longwall shields predicts leakage penetration near the headgate part of the face and enhanced flow in the loosely compacted gob near the face. The model results are consistent with general observations and calculations for flow paths and velocities reported in the literature.

A second example shows the unfavorable effect of a gob gas venthole intersecting the gob area. The model results indicate that the venthole will attract mine air, resulting in reduced methane production. These results are consistent with empirical observations and measurements reported in the literature.

It is concluded that the methodology presented in this paper provides an improved method for estimating the permeability distribution in the gob behind a longwall face. The methodology allows realistic numerical experiments to be conducted for site specific cases to enhance the safety and effectiveness of methane mitigation techniques.

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