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A REVIEW OF OVERBURDEN FRACTURING AND CHANGES IN HYDRAULIC CHARACTERISTICS DUE TO LONGWALL MINING

Hadi Nourizadeh1, Ismet Canbulat2, Joung Oh2, Chengguo Zhang2, Naj Aziz3, Ali Mirzaghorbanali4, Kevin McDougall4

ABSTRACT: Longwall mining is a major mining method to extract thick, flat-lying and extensive seams. Due to the nature of this mining method, the overlying strata move continuously downwards into goaf and as a result, surrounding rocks are distressed, deformed and fractured. In the near area above the mined coal seam, both vertical and horizontal fracturing networks are evident, however within the higher zones, bed separation and slippage are the dominant displacements. The enhanced cracks alter hydraulic characteristics (porosity and permeability) of the rock mass, consequently disturbing the groundwater and surface water flow regime. There have been various techniques utilised to study mining-induced fracturing mechanisms and changes in water flow systems. They mainly include empirical, physical, analytical and numerical approaches. Of note is that due to the complexity of the issue and difficulties in the implementation of costly and time-consuming in-situ measurements, currently, numerical simulation is a popular approach. The aim of this review paper is to present the current state of the art in mining-induced goaf overburden fracturing and its interaction with groundwater and surface water.

INTRODUCTION

When the coal seam face advances forward, the overlying strata above the mining area caves into the voids resulting in deformation of rock masses, opening pre-existing discontinuities and noticeable changes in the hydraulic properties including porosity and associated permeability of the field. Mining-induced fracturing can create a potential path to penetrate aquitards into the goaf, which may result in serious hazards such as water-inrush and fluids. These incidences severely threaten the safety, efficiency, and economy of the mine. Therefore, a good understanding of the initiation, propagation and development of fractures in overlying strata is highly important to implement efficient, safe, and environmentally friendly mining (Wang et al., 2017). Several empirical and in-situ measurement studies have been conducted to simulate the rock deformation and fluid flow in the disturbed rock masses above longwall mining panels. Although these studies are very valuable, there is still difficulty in clearly understanding of rock fracturing and fluid flow mechanisms in the overburden strata, which is mostly because of anisotropic and heterogeneous nature of rock mass properties and the effects of panel geometry. Conversely, the interactive relationships between rock deformation and fluid flow involving highly complex spatial and temporal variations may only be studied accurately through numerical methods. A well numerical model is able to successfully simulate a highly complex problem with true and reliable results. Numerical methods significantly reduce the time and expense of research(Zhang and Sanderson, 2002a). Problems related to the rock mass, which
is subjected to loading, can be solved numerically through a continuum and/or discontinuum methods. The models differ in representation ways of the heterogeneity of a fractured medium. Common continuum methods may explicitly estimate enhanced permeability through plastic strains; however, they are not able to directly trace aperture on flow path or predict connectivity of fractures (Poulsen et al., 2018). It is broadly believed that the discontinuum methods such as DEM would be the most reliable method to imitate the response of discontinuous rock mass against loading and excavation.

**THE HYDRO-MECHANICAL RESPONSE OF OVERBURDEN ROCK MASS TO LONGWALL MINING**

The structure and component of the crustal rocks are generally complex, heterogeneous and anisotropic that make the formulation and determination of the real behaviour rocks more challenging. Fractures are ubiquitous in the earth's crust on all scales from micro-scale to macro-fractures along bedding planes, faults and shear zones. Study of fractures is essential in different engineering fields as they play a substantial role in rock deformation and more importantly, they are major paths for fluid flow in both permeable and impermeable rock masses. Excavation in stratified rocks causes changes in-situ stresses leading to various deformation such as shear fractures, separation and bedding planes, tensile fractures, opening pre-existing joints.

During and after extraction of coal seams by longwall mining, the immediate roof above the panel bends and moves downwards into the void. This movement causes bending and deformation of overlying strata. Additionally, delamination and separation of bedding planes are probable. In a vertical profile of longwall mining, rock mass deformation commences from the mined seam and propagates upwards, however; strata located below the seam may also be affected and deformed. At the first stage of the deformation process, closer layers to the void separate from upper-laying layers, bend and then fracture. The process of overburden deformation (e.g. shearing, delamination and, bending) continuously extends further upwards as mining face advances. Ceasing of ground movement can complete in from a few hours to several years. In general, overburden response to the longwall mining strongly depends on the location and thickness of the overlying strata, as well as mining geometry.

This incident substantially changes the hydraulic properties of the overburden rocks such as void fraction (fissure ratio, porosity, and fracture ratio) and permeability. Figure. 1 shows the various void fractions (fissures, fractures, pores) associated with longwall mining (Wang et al., 2016b).

Importantly, the induced voids may connect catchments, aquifers, and goaf together that may cause significant economic and safety issues on mining operations such as rushing huge volumes of water into the mining panel (Islam and Shinjo, 2009).

In general, disturbed overlying strata are divided into three to four distinct zones in each of which fracture and deformation characteristics are similar. Researchers have endeavored to determine the height of these zones being mostly based on-site observations. The heights of these disturbed zones are dependent on geometry and mechanical properties of the overlying strata, as well as coal seams.

The thickness of coal seams and overburden have a direct influence on the height of disturbed zones compared to Poisson ratio, elastic modulus, bulking factor and UCS which have an inverse influence on this height (Rezaei et al., 2015). Additionally, the caving process of overburden can also vary between short and long time scales (Majdi et al., 2012). The overburden cave-in process associated with underground mining significantly alters the regional water flow regime, with impacts to a distance of several kilometers (Tammetta, 2013).
The impacts of underground coal mining on the hydrological behavior of disturbed overburden have been extensively studied by vast in-situ permeability measurements which reveal that the permeability of rock masses significantly increases in particular parts of overburden (Tammetta, 2015, Khanal et al., 2019, Zou et al., 2012). More importantly, the induced voids may connect catchments, aquifers, and goaf together that may cause significant economic and safety issues on mining operations such as rushing huge volumes of water into the mining panel (Islam and Shinjo, 2009).

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Impacts can be in the forms of drainage of surface and sub-surface into the goaf and mining area, alteration aquifers, and water quality as well. The evolution mechanism of fractures induced by longwall mining beneath gullies, lakes, catchments, and near aquifers is of great importance as the fractured zones may be developed to these water resources causing severe safety and efficiency problems to the underground mining (Peng, 2006). This issue becomes even more severe, when the coalfield is located in a sensitive ecological environment. The delamination of strata enhances the horizontal permeability of rock media; however, vertical fractures also increase the vertical permeability and it gradually decreases with the increase of

Figure 1: A schematic overview of overburden strata response to longwall mining and the potential deformations (Wang et al., 2016b)
distance from the mining area. According to the previous studies, in the stratified roof near the longwall mining area, hydraulic conductivity (both vertical and horizontal) intends to extend leading to considerable water drainage to the gob. Conversely, the major change in the hydraulic properties of the higher zones is the horizontal conductivity.

MODELLING OF DEFORMATION OF OVERLYING STRATA AND CHANGES IN HYDRAULIC CONDUCTIVITY ABOVE LONGWALL PANELS

Several empirical and analytical models have been introduced to simulate mechanical responses of stratified rocks to the in-situ stress alteration due to longwall mining. Furthermore, various numerical modelling techniques have been presented to study the reaction of overburden rocks to longwall mining. Fracturing mechanism of rock mass and subsequently changes in permeability are highly non-linear functions of redistribution of initial stresses due to mining. Various equations have been proposed to calculate the permeability of intact or fractured rocks. However, there is not a general consensus on the formulation of the interaction between rock deformation and permeability changes. Fluids may not flow uniformly within fractured rocks as the hydraulic characteristics (e.g. aperture) of the rock media control its transmissivity. In general, the hydraulic response of rock mass is controlled by the geometric properties of the fracture networks. Rock deformation is considered to have fundamental effects on fluid migration due to alteration of discontinuity geometry including closing and/or opening of fluid conduits, as well as creating new ones. In this section, the current state of the art in the modelling of the longwall-mining induced fracturing and the resulting changes in permeability will be presented.

Empirical models

Various empirical formulas have been proposed to describe the height of rock fracturing due to longwall mining mostly based on extensive field studies,(Xu et al., 2017, Majdi et al., 2012). However, these formulas are highly simplified and consider only a few effective factors (e.g. coal seam thickness and mining height), but do not reflect the effects of the other significantly influential geo-mechanical properties of rock masses. For example, the State Bureau of Coal Industry of China proposed some empirical formulas based-on thousands of in-situ measurements for estimation of the maximum height of the fractured zone above longwall mines. In the proposed empirical formulas, the average compressive strength of overburden strata as a lithological characteristic and thickness of mining coal seam have been considered as the basic variables. The maximum height of fractured zones can be calculated from the following equations (Table 1). In the proposed formulas, \( H_i \) is the maximum height of the caved zone and \( \sum M \) is the height of coal seams(Wang et al., 2016a).

Table 3- The empirical equations for estimating the height of the maximum caved zone

<table>
<thead>
<tr>
<th>Lithological conditions</th>
<th>Appropriate equation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard overburden</td>
<td>( H_i = \frac{100 \sum M}{12 \sum M + 2.0} \pm 8.9 )</td>
</tr>
<tr>
<td>Mid-hard overburden</td>
<td>( H_i = \frac{100 \sum M}{1.6 \sum M + 3.6} \pm 5.6 )</td>
</tr>
<tr>
<td>Weak overburden</td>
<td>( H_i = \frac{100 \sum M}{3.1 \sum M + 5.0} \pm 4.0 )</td>
</tr>
</tbody>
</table>

In Australia, prediction of the height of caving has been widely studied by many researchers and several empirical models have been established to determine the height of fracturing. The proposed models are generally based on in-situ measurements using extensometer and piezometer tests(Ross and Sutton, 2016). The proposed empirical formulas by Ditton and Merrick (2014) and Tammetta (2013), are the most common approaches used in Australia for
prediction of the height of fracturing induced by longwall mining. The results of these studies are summarized in Table 2. The height of desaturation in Ditton and Merrick’s study implies the connective fracturing and complete water drainage in the goaf.

Field measurement-based techniques suffer from an executive restriction mainly because of being costly and time-consuming. However, the combination of gained field-data from this approach with numerical simulation methods would be the best approach to study the response of rock masses to longwall mining. The success of a mechanical model to identify the behavior of rock masses to any change in the ground such as excavation strongly depends on the validity and reliability of the stress-deformation behavior of the rock masses.

Table 4- Developed models for prediction of the height of fracturing above longwall mining in Australia

<table>
<thead>
<tr>
<th>Study</th>
<th>Main Conclusion</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ditton and Merrick (2014)</td>
<td>( H_{od} = 1438 \ln \left(4.315 \times 10^{-5} U + 0.9818\right) + 26 )</td>
<td>HoD: Height of Desaturation ( U ): a variable, ( W ): panel width ( T ): mining height, ( H ): cover depth</td>
</tr>
<tr>
<td>Tammetta (2013)</td>
<td>Zone 1: up to 20 m above coal seam Zone 2: up to 1 ( W ) Zone 3: 1.0 – 1.6 ( W ) Zone 4: 1.6 ( W ) – 3 ( W ) Zone 5: &gt; 3 ( W )</td>
<td>Zone 1: Caved zone Zone 2: Large movement zone Zone 3: Vertical dilation Zone 4: Vertical relaxation Zone 5: No disturbed zone ( W ): Panel width</td>
</tr>
</tbody>
</table>

Conceptual models

Conceptual models seek to interpret phenomena and behaviour of rock mass in terms of the process involved, with little quantitative description(Zhang and Sanderson, 2002b). Conceptual modelling of the hydro-mechanical behaviour of rocks excessively relies on analytic solutions and interpretation of in-situ measurement data. The results of such models are highly idealized and contain a less quantitative description of the problem. However, these models are a common approach to interpret the response of ground to longwall mining. In such models, the affected rock mass is divided into distinctive zones in which rock behavior and deformation characteristics are equivalent.

Peng (2006) proposed a conceptual model, which divides strata above longwall panel into four zones including caved zone, fractured zone, continuous-deformation zone, and soil zone (Figure. 2) (Peng, 2006). In the caved zone, fractures appear spatially and so immediate roof breaks into different sizes and shapes. Strata in the immediate roof sag downwards and when sagging process reaches the maximum allowable limit, the strata are fractured and broken into different sizes. The phenomenon of overburden collapsing continues until the gap between rock layers is less than the maximum allowable limit. This gap decreases upward as the volume of broken rocks increases compared to the volume of in-situ rocks. Thus, the height of caving zone can be obtained by Eq.1:

\[
h_{im} = \frac{H - d}{k - 1}, \quad d \leq d_0
\]
Where; \( h_{im} \) is the height of caving zone, \( d \) is sagging of the un-caved strata, \( d_0 \) is maximum allowable limit, \( H \) is mining height, and \( k \) is the bulking factor of the broken rocks and can be defined as the ratio of the volume of the broken rock to the original volume of the same rock.

The height of the caved zone can extend up to 2 to 8 magnitudes of the mining height. In the fractured zone, both vertical fractures and bedding separation can be seen, however, due to the presence of horizontal forces, separated blocks are in contact. The height of the fractured zone is estimated between 28-58 times the mining height. In the continuous deformation zone, rock masses go under a sort of moderate deformation accompanied by bedding separation, however, there is no significant vertical cracking compare to the lower zones. In the soil zone, opening and closing of the cracks are obvious depending on the location of the extracted panel.

Gale (2008) reported that both vertical and horizontal fractures are substantial, however in the fractured and continuous deformation zones, horizontal cracks are the dominant deformation and the density of the vertical fractures decreases with an increase in the distance from the mining panel (Gale, 2008). The height of complete groundwater drainage above longwall panels has been broadly studied using piezometers tests and extensometer tests. The results of these field tests have contributed researchers to propose several conceptual models for hydraulic conductivity (K) changes (Tammetta, 2013). Kendorski (2006) proposed a conceptual model with distinctive zones showing the impacts of longwall mining on water flow in the deformed overburden above mined voids (Kendorski, 2006). In another research, Foster and Enever (1992) produced a model that shows the hydrological response of overburden to longwall mining. This model was derived from piezometer data (Figure. 3).

![Figure 2: The profile of fractured-roof above longwall mining (Peng, 2006)](image)

![Figure 3: Hydro-mechanical responses of overlying strata to longwall mining](image)
Tammetta (2015) conducted a study to investigate changes in hydraulic conductivity above longwall panels using the direct measurement of pre-mining and post-mining K (Tammetta, 2015). The database consisting of 799 measurements from 18 separate sites worldwide was used to identify K change trends. Finally, a quantitative conceptual model was presented based on the analysis of the obtained database. Figure 4 shows a generalized cross-section for the ratio of the post-mining K to pre-mining K (R) over a longwall panel. In the disturbed zone, there is a moderate increase in the hydraulic conductivity which indicates that the majority increase in the post-mining K occurs in the horizontal direction mainly along the bedding planes. However, the large increase in the post-mining K in the caved zone demonstrates that vertical components of pre-mining K undertake a significant increase in this zone. Additionally, it is concluded that small differences between pre-mining and post-mining K around chain pillars can be due to the concentration of the vertical stresses in this neighborhood (Tammetta, 2013). Figure 5 shows pre and post-mining hydraulic conductivity of rock masses above a longwall panel obtained by packer testing at the Dendrobieburn Mine. As can be seen from Figure 5, pre-mining and post-mining regional K is highly dependent on the lithology and depth of the cover. In general, post-mining K is seen to be 3-10 times of magnitudes higher than the one of pre-mining. However, deeper parts typically experienced a greater increase in K.

Kendorski (2006) proposed a generalized model to conceptually demonstrate the effects of underground mining on the caving process and permeability changes of overburden (Figure 6). According to this model, overlying strata are divided into five zones in terms of caving mechanisms comprising; caved zone, fractured zone dilated zone, constrained and unaffected zone, and surface disturbance zone. However, in terms of permeability changes the overlying strata consist of three major zones; lower zone, middle zone, and upper zone. The lower zone is highly affected by subsidence and as a consequence vertical permeability increases significantly. This zone comprises of the coved zone and fractured zone. In contrast, the middle zone (including dilated zone) suffers from a considerable increase in horizontal permeability. Finally, the upper zone is not affected by mining and subsidence deformation in terms of permeability changes (Kendorski, 2006).
Numerical models

Modern development in the use of computers and particularly in the implementation of numerical modelling has provided powerful and reliable approaches. Due to the complexity of rock behaviour, analytic methods with the inevitable high number of assumptions are not able to reproduce exact solutions. However, successful numerical methods may establish predictive behaviour with acceptable approximations. Numerical methods significantly reduce the time and expense of research particularly in the field of natural processes, though limited experimental investigations are required for calibration of these models. Many powerful computational tools are readily available on the markets with different computer codes for simulation and evaluation of the behaviour of rocks. The fundamental difficulty in studying the rock behaviour, by any means, is that the physical and mechanical properties of rock mass are defined by nature. More importantly, rock media are highly discontinuous, heterogeneous and anisotropic. All these inherent characteristics along with the presence of fracture and fluid create a highly complex environment for mathematically studying through numerical methods. Even more crucial, a perturbation in in-situ stresses due to the man-made excavation will result in creating new fractures and opening pre-existing fractures (Jing et al., 2013, Jing, 2003). The simulation of rock mass behaviour by numerical models can be conducted on the basis of discontinuum methods (DEM, or DFN), continuum methods (FEM, BEM or FDM), and hybrid methods. Several factors affect the selection of the modelling methods (continuum and/or discontinuum) such as the aims of modelling, problem scale, and geometry of discontinuities. Due to the implementation simplicity of continuum modelling, it is very popular and common in the simulation of fluid flow and transport in fractured rocks. There are a number of computer codes using FEM and/or FDM methods in two or three-dimensional such as MODFLOW, FLAC 2D, FLAC 3D, COSFLOW, and etc.
Khanal et al. (2019) developed a numerical model using a coupled 3-D mechanical deformation and double multiphase flow finite element code, COSFLOW to investigate the impacts of underground mining on permeability changes of overburden strata (Khanal et al., 2019). The model demonstrates that an increase in the longwall panel width will contribute to enhanced permeability. The results demonstrate that there is a significant increase in the permeability up to 60 m above the coal seam before the mining face reaches the monitoring position. In another study, Khanal et al. (2018) again applied COSFLOW to investigate the progress of connective fractures and water conductivity induced by longwall mining in a coal mine in Australia (Khanal et al., 2018). The results show that there is a significant in the post-mining hydraulic conductivity of the immediate roof.

Common continuum-based methods implicitly solve the rock deformation and hydraulic equations; however, they are not able to directly trace fractures and aperture on flow path to predict fractures connectivity. discontinuities such as faults, joints, bedding planes and cleats which paly substantial rules in rock deformation, rock fracturing, and fluid flow regimes, are not explicitly defined in the continuum methods. Therefore, discontinuum-based methods such as DEM and DFN would be only computational simulations to explicitly solve such a complex problem. Presentation of Discrete Element Method (DEM) engendered a significant development in rock mechanics. In DEM methods, a problem domain is usually composed of an assemblage of blocks or particles surrounded with contacts (discontinuities) which must be continuously identified during deformation process by representing suitable constitutive laws. Several computer codes based on DEM have been represented to model the behaviour of rock masses. The most representative codes are UDEC and 3DEC for two-dimensional and three-dimensional problems for blocky systems and PFC 2D and PFC 3D for granular materials represented by Itasca Consulting Group Ltd.

Poulsen et al. (2018) presented a numerical bounded-particle model (BPM) using the PFC in which fracture initiation and propagation, fractures connectivity, and aperture in disturbed overburden above a coal mining panel were calculated in a piecewise manner (Poulsen et al., 2018). Although particle-based models may be able to simulate the response of rock masses to a perturbation due to excavation, the calibration of micro-particle properties to the macro-properties, and the computational time remains as two major challenges using bounded-particle-based methods. Furthermore, several useful coupled hydro-mechanical DEM models using Universal Distinct Element Code (UDEC) have been applied to identify the progressive fracture process and fluid flow within fractured rock masses due to longwall mining.
Shabanimashcool et al. (2014) carried out discrete numerical modelling using the UDEC to investigate the caving mechanism of overlying strata above a longwall panel in the Svea Nord coal mine (Shabanimashcool et al., 2014). The study demonstrates that displacement increases with the coal face advance. The maximum deflection is 2.5 m when the coal face advances 30 m. In addition, the results of the numeral modelling show that the horizontal stresses reach to the maximum magnitudes when the coal face advances to a distance of 35 m and then the immediate roof started to fail in buckling. Gao et al. (2014) presented a 2D numerical model using the UDEC Trigon approach to simulate the caving mechanism of overlying strata in the German Ruhr coalfield (Gao and Stead, 2014). According to the results, compressive shear failure is the dominant mode of failure rather than tensile failure. The model results show that at the first stage when the width of the stope is 12 m, only a few fractures are generated. However, as the face advances, fractures are extended wider and deeper. When the face advances 60 m the first cave-in occurs. When the face advances more, higher layers also collapse and fall down. A key stratum or primary key stratum plays a substantial role in controlling subsidence of cap overburden. The strength and thickness of the key stratum govern the greatest fracture length among the entire overlying strata. Wang et al. (2017) proposed a theoretical model for calculation of the void ratios of fractures (VRFs) considering the key stratum theory. In addition, a DEM numerical modelling was designed using UDEC and the results show that when the mining face is in the distance of 100 m, fractures mostly come up near abutments and in the centre of the distressed strata. However, when the coal face passes this distance, the fractured zone was concentrated between the two key strata presenting an arch type zone. Wang et al. (2016) adopted the UDEC to investigate the height of fractured zone and the evolution mechanism of fractures in shallow coal seams beneath gully topographies (Wang et al., 2016a). The numerical simulations show that the mining height has a demonstrational effect on the evolution of fractures. When the height of mining is assumed to be 4.0 m and the coal face advances of 90 m (still the coal face is behind the gully), the interconnected bed separations and vertical fractures occur on the strata above the mining-out area.

DISCUSSION AND CONCLUSIONS

In order to have an efficient, safe and economic underground mining a fully quantified and predictive method is required to determine the overburden deformation mechanism. The mining-induced deformation and resultant changes in hydraulic conductivity have been widely studied. Traditional methods such as empirical and conceptual methods, may not convince modern regulations, nor reflect the effects of geological, hydrological and geomechanical conditions (Poulsen et al., 2018). These rule of thumb studies may not provide a reliable investigation for the impacts of longwall mining on the environment. On the other hand, a well numerical model is able to successfully simulate a highly complex problem with true and reliable results. Among the existing numerical methods, many researchers concluded that the continuum methods such as the finite element method and finite difference method may not be appropriate and accurate approaches to numerically simulate the behavior of overlying strata and ground surface movements because of anisotropic and heterogenic properties of the rock mass. Common continuum-based methods implicitly solve the rock deformation and hydraulic equations; however, they are not able to directly trace fractures and aperture on flow path to predict fractures connectivity. More importantly, discontinuities such as faults, joints, bedding planes and cleats, which play substantial rules in rock deformation, rock fracturing and fluid flow regimes are not explicitly defined in the continuum methods. To provide a reliable and precise study, the effects of discontinuities in the problem domain, the geometry of longwall panel layout, the surface topography, the surface, and sub-surface water resources must be considered in the investigation which may only be possible through discontinuum methods. Although several discontinuum-based models have been applied to solve such a complex problem, there is still
a need to develop a robust coupled hydro-mechanic model that can properly represent the fracture development and fluid flow within fractured rock masses in an optimal manner.

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