A review of roof instabilities associated with Longwall Top Coal Caving

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ABSTRACT: Longwall Top Coal Caving (LTCC) is a thick coal seam mining method which uses the Single Pass Longwall (SPL) method for extracting the lower section while the upper section (top coal) is mined by means of caving. The mining height in LTCC, compared to other methods, may result in roof instabilities such as caving and weighting. The understanding of roof instabilities involved in LTCC, however, is limited and the applicability of conventional rock mass stability assessment systems into LTCC can be questioned. This paper presents a systematic review of the LTCC-associated roof instability mechanisms and the applicability of widely-applied rock mass classification systems into LTCC. The study confirms that the vertical stress redistribution caused by LTCC is in general similar to that caused by SPL; the predominant failure mode in roof rock mass can be either shear or tension while the controlling failure mechanism in top coal is shear; the movement of immediate and main roofs in LTCC is similar to that in SPL; conventional rock mass classifications can be applied in assessing LTCC roof stability however their sensitivity to coal stability is low. The paper's findings can assist engineers in better applying and managing LTCC operation.

1. INTRODUCTION

The Longwall Top Coal Caving (LTCC) method divides a thick coal seam (whose thickness is greater than 4.5 m) into two sections: the lower or cutting and the upper or top coal. The lower section is extracted by conventional Single Pass Longwall (SPL) method and the top coal is recovered by means of caving through face support (Fig. 1). LTCC has significant advantages compared to other methods in extracting thick coal seams, as reviewed in Le et al. (2017a). In this paper, the roof strata to be studied are limited to the immediate roof and main roof. The immediate roof is the portion of the strata lying immediately above top coal. Immediate roof can fail and cave immediately, or with little delay as support advances. Above the immediate roof, the strata in the lower portion of fractured zone is called the main roof. Main roof can fail, but normally will not cave, and can still transmit horizontal force through broken strata (Fig. 1).

The increased mining height in LTCC, compared to other longwall mining methods, may cause increasing risks of strata instabilities such as first caving of top coal/immediate roof (strata start to cave) and weighting of main roof strata. A delay in first top coal caving indicates a source of top coal loss while a delay in roof strata caving or weighting gives rise to risk of sudden collapse or severe weighting event. This can consequently lead to injury/fatality to mining personnel and damage to equipment. Therefore, a thorough understanding of roof instabilities associated with LTCC has an important role in the successful operation of the method. Additionally, although conventional rock mass classification systems have been used to assess the stability of underground excavation span, the applicability of these systems in assessing top coal and roof stability in LTCC can be questioned and should be analysed.

Fig. 1 Roof strata in Longwall Top Coal Caving face (Vakili, 2009).

The geotechnical mechanisms involved in roof instabilities such as stress distribution, coal and rock failure, strata deformation, roof weighting and top coal caving caused by LTCC mining have not been systematically understood in the literature. This paper presents an in-depth review of the above mechanisms involved in not only LTCC but also SPL operations since LTCC uses SPL for extracting the lower section of coal seam. The applicability of widely-applied rock mass classification systems into LTCC mining is described. A systematic understanding of LTCC roof instabilities is obtained, which can assist engineers in better applying this efficient and productive thick seam mining method.

2. MECHANISMS INVOLVED IN LTCC ROOF INSTABILITIES

2.1. Stress distribution

Prior to an underground extraction, rock is subjected to an initial equilibrium state of stress. The mining causes a new stress distribution that directly affects the potential rock mass failure as well as strata movement, weighting and caving. For conventional longwall mining, the stress distribution has been mostly focused on the magnitude and location of peak abutment stress (Whittaker, 1974, Peng, 2008, Brady and Brown, 2004). Similarly, for LTCC, a few studies have investigated the vertical stress redistribution. Xie et al. (1999) conducted a numerical analysis for a Chinese LTCC face where the horizontal stress was twice the vertical stress. The authors found that the peak abutment pressure was located about 6 m ahead of coal face while the abutment pressure reached 40 m ahead of coal face. Yasitli and Unver (2005) studied a Turkish LTCC face where the vertical stress was the major principal stress. The study found that the peak abutment stress was formed at 7 m away from coal face and was 2.5 times the initial field stress. In general, the magnitude and location of peak abutment stress induced by LTCC mining are within the ranges of those induced by SPL mining (Figs. 2–3). Study on the horizontal stress redistribution caused by LTCC, however, is preliminary and very limited (Le et al., 2017b). The breakage and/or caving of roof strata dramatically change roof pressure, as reviewed in Section 2.3.

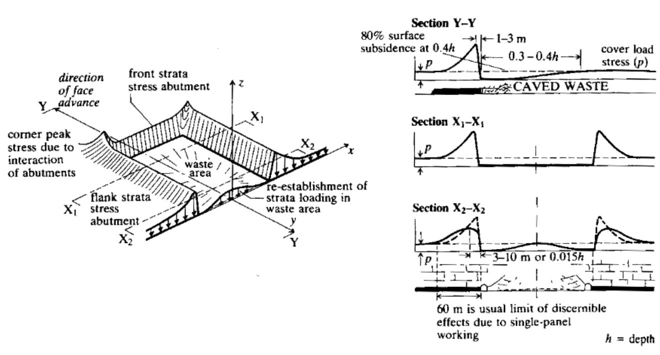

Fig. 2 Vertical stress redistribution around a UK SPL panel (Whittaker, 1974).

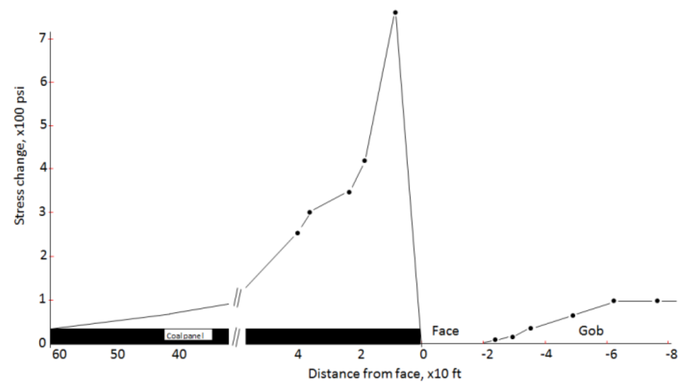

Fig. 3 Front abutment stress versus SPL face distance (Peng and Chiang, 1984).

2.2. Roof rock and top coal failure

The stress redistribution induces tensile fracturing, de-lamination and opening of pre-existing fractures, and the shear fracturing/slip on bedding planes and on natural and mining-induced discontinuities in the surrounding rock mass (Brady and Brown, 2004). Kelly et al. (1998) stated that in previous conventional longwall studies, the predominant failure mechanism ahead of coal face was tensile failure. This tensile failure was formed by an indirect tensile stress due to an essentially unconfined large abutment load close to the face. However, several longwall studies conducted in Australian coal industry (Kelly et al., 1998, Kelly et al., 2002, Gale, 2004) concluded that the predominant rock failure modes are shear fractures of intact rock and beddings, especially above and ahead of longwall face. In strong and massive roof strata, they found that tensile failure may develop and dominate shear failure.

The failure of top coal in LTCC mining has been analysed in several studies. Xie et al. (1999) stated that top coal starts to move where the front abutment stress reaches its peak value. The failure zone is limited to 2 m ahead and above the face line due to the high strength of coal in the studied panel. Yasitli and Unver (2005) modelled the state of failure in an LTCC face. The corresponding numerical result confirms that shear failure is the predominant mechanism ahead of the face (Fig. 4). Le et al. (2017b) further concluded that the predominant failure mode in roof rock mass can be either shear or tension while the controlling failure mechanisms in top coal is shear.

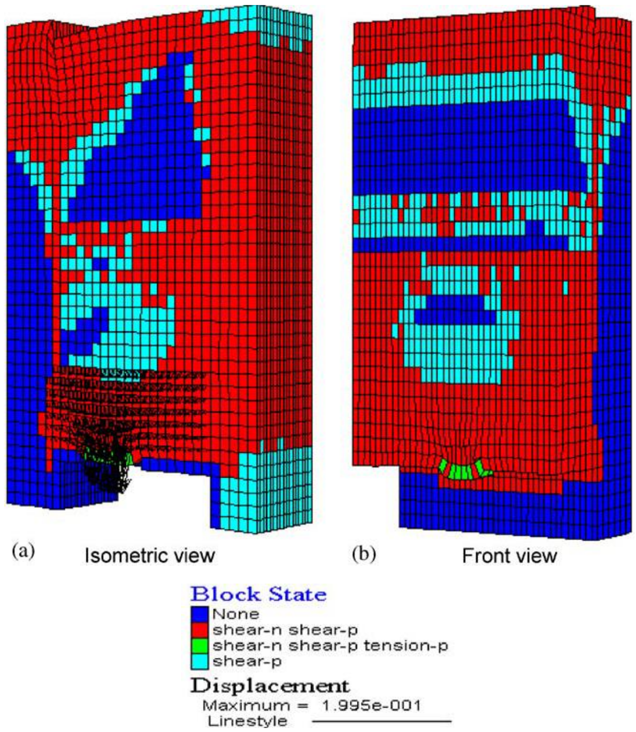

Fig. 4 Vertical state of coal failure during caving (Yasitli and Unver, 2005).

2.3. *Roof strata movement and weighting*

There are two distinctive phases of immediate and main roof movement above a conventional longwall face (Peng and Chiang, 1984). The first phase includes the distance from the face set-up entry to the point where a large-area caving of immediate roof (or rupture of main roof) occurs. The change in roof pressure associated with the caving/sagging is referred to as the first weighting. The second phase commences after the first weighting and extends to the end of panel extraction. As the face advances, the cyclic breakage of immediate and main roofs results in cyclic increase and decrease in roof pressure at the face, which is called the periodic roof weighting. The movement of roof strata in LTCC has been considered similar to that in SPL (Vakili, 2009, Galvin, 2016). A large-scale LTCC computer model developed by Le et al. (2017b) confirmed this similarity. Le et al. (2017b) also stated that the roof strata rupture in crushing mode during their first weighting (Fig. 5).

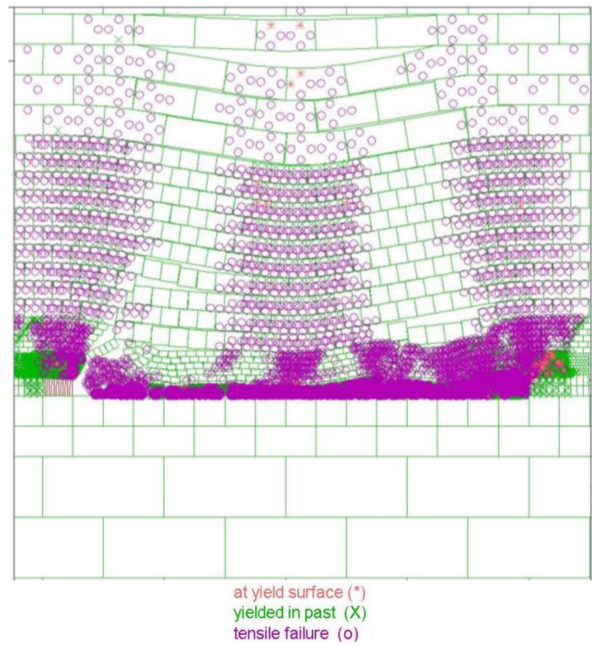

Fig. 5 Rock block failure in the first weighting of roof strata (Le et al., 2017b).

2.4. *Top coal deformation and caving*

It is agreed that there are four zones of coal seam deformation and fracturing in LTCC mining (Xu, 2004, Humphries et al., 2006, Wang et al., 2014), as shown in Fig. 6. Zone I is the intact or elastic deformation zone that is located ahead of the peak vertical stress. Zone II is the fracture development zone or compression zone that is located between the peak vertical stress and the face line. In this zone, coal is broken and initial fracturing is generated. Zone III is the fracture extension or loosening zone located above the roof canopy. In this zone, the top coal fractured in Zone II is further broken due to the action of face support. Zone IV is the caving zone that is located above and behind the rear canopy. The lower portion in this zone (IV1) is broken into small blocks and is easily drawn. The upper portion (IV2) is often compressed into an arch and can be drawn by swinging the articulated rear canopy.

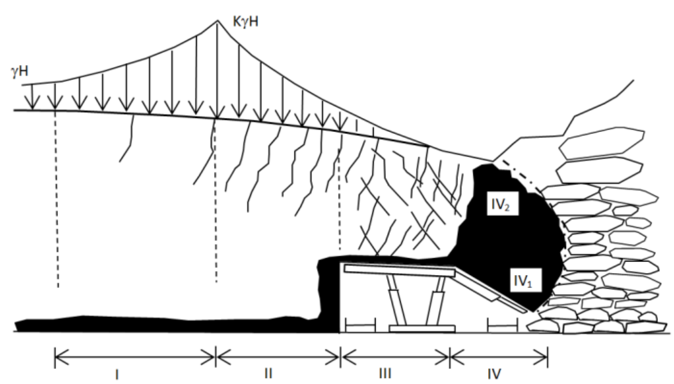

Fig. 6 Coal seam deformation and fracturing in LTCC mining (Humphries et al., 2006).

According to Brown (2002), caving occurs as a result of two major influences including gravity and mining-induced stress. Depending on the relationship between the induced stress, rock mass strength, and geometry and strength of discontinuities, the caving mechanism can be "gravity caving", "stress caving" or a third general case. As found by Le et al. (2017b), the mechanism of first top coal caving can be attributed to "stress caving" since the predominant failure mechanisms are the brittle fracture of intact rocks and slip on discontinuities (Fig. 7). It is noted that for a highly jointed rock mass such as coal measure rock, there is an assumption that coal/rock caving is mainly controlled by discontinuities (Vakili and Hebblewhite, 2010). The caving can occur in four conceptual models: bulking factor; vertical discontinuities; horizontal discontinuities; and combined horizontal-vertical discontinuities.

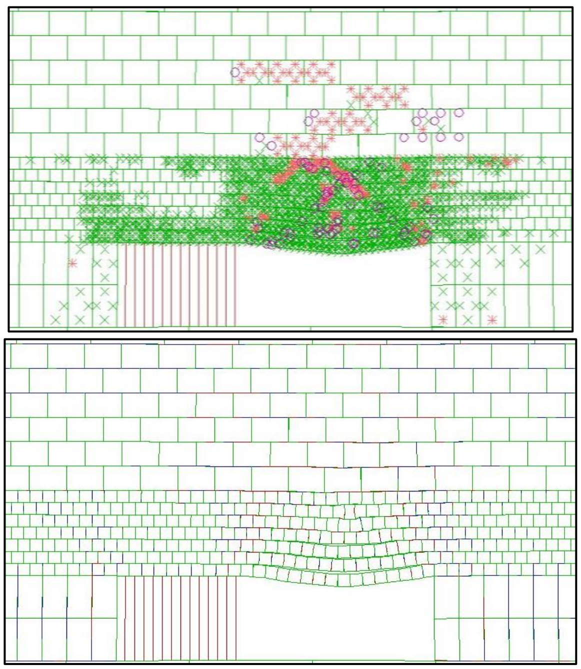

Fig. 7 Failure in top coal before first caving (Le et al., 2017b). NOTE: blocks that fail in current shear, past shear and tension are illustrated by red star *, green X and purple o, respectively; discontinuities that have opened and slipped are in red and blue colour, respectively.

3. REVIEW OF THE APPLICABILITY OF ROCK MASS CLASSIFICATION SYSTEMS FOR LTCC MINING

3.1. Rock Mass Rating (RMR) system

The Rock Mass Rating (RMR) system was developed by Bieniawski (1973) for the tunnelling industry in South Africa to assess the stand-up time of unsupported excavation span. More details of the RMR development and application can be found in Bieniawski (1989), Hoek et al. (1995) and Bieniawski (2011). The database for the development of RMR was mainly based on civil excavations predominantly in sedimentary rocks with less than 500 m depth of cover. Bieniawski (2011) argued that RMR continues to be used successfully even for very poor rock (RMR<20). Hence, RMR can be applied for the stability assessment of underground coal excavations. For application in the mining industry, RMR has been adapted for block caving mining (Mining Rock Mass Rating system) and for coal mining roadways (Coal Mine Roof Rating).

3.2. Mining Rock Mass Rating (MRMR) system

The Mining Rock Mass Rating (MRMR) system was developed based on the RMR system by Laubscher (1977) for the cavability prediction and stability assessment in block caving mining. More details of the development and application of MRMR can be found in Laubscher (1993), Laubscher and Jakubec (2001) and Laubscher (2001). Recently, Suorineni (2014) noted that there is a risk in using MRMR for block caving assessment. This is mainly due to the use of the RMR database that is biased towards sedimentary rocks at shallow depths. Contemporary block caving is operated in metamorphic and igneous environments and at greater depths. The risk is that MRMR may overestimate the cavability of a real mining.

3.3. Extended Mathews stability graph

The Mathews stability graph was developed by Mathews et al. (1981) for assessing the stability of open stope in hard rock mining. The graph has been significantly modified over the years in which the extended graph according to mining method (Suorineni, 2014) contains data of not only open stope but also narrow vein, sublevel caving, block caving, cut-and-fill and longwall mining methods (Fig. 8). It is seen from the figure that there seems to be lack of the longwall data in the "Stable" and "Cave" zones. Thus, the applicability of the extended Mathews stability graph for assessing excavation stability in longwall mining is doubtful.

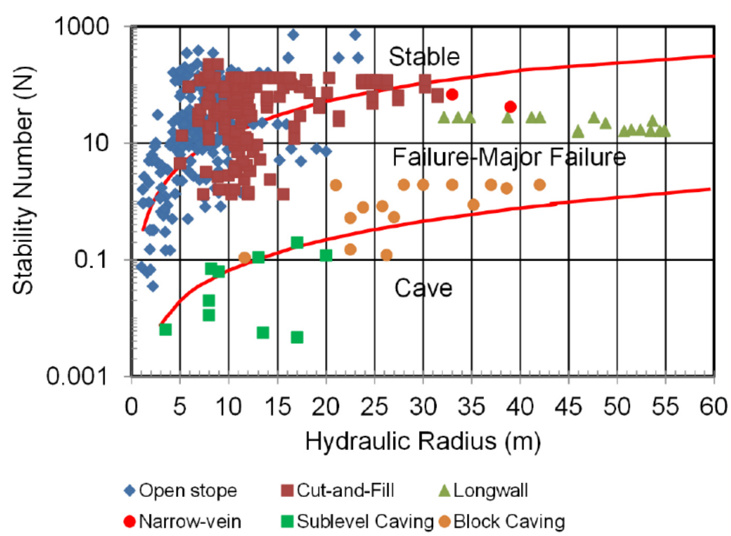

Fig. 8 Composition of the extended Mathews stability graph database by mining method (Suorineni, 2014).

3.4. Coal Mine Roof Rating (CMRR) system

The Coal Mine Roof Rating (CMRR) system was developed by Molinda and Mark (1994) to meet the need for a rock mass classification readily applicable for coal mining. The CMRR system was derived from the database of coal mines in US, using the similar format of the RMR system. Detailed procedures for the data collection and implementation of CMRR is presented in Mark and Molinda (2005). The applications of CMRR into longwall mining can be seen in some mine design tools and two case studies (Table 1) The CMRR system, in essence, is a roof rock strength indicator rather than a rock mass stability indicator (Calleja, 2008). Its applications in assessing coal roof stability are mostly limited to roadways. Application of CMRR in assessing top coal/roof stability in LTCC face thus requires further investigation.

Table 1. Applications of CMRR (Mark and Molinda, 2005)

CMRR application	Product or type of application
Analysis of Longwall Pillar Design (ALPS)	Design tool
Australian Longwall Tailgate Serviceability (ALTS II)	Design tool
Analysis of Roof Bolt Selection (ARBS)	Design tool
Stability of extended cuts	Case study

3.5. *Classification systems based on longwall mining*

Rock mass classification systems derived from longwall mining are more readily applicable to LTCC mining. Based on conventional longwall operation, a number of systems have been developed to predict the first and periodic caving/weighting of roof strata. Due to the similarity in roof strata movement between SPL and LTCC (see Section 2.3), these systems can also be used in assessing LTCC roof instability. For detailed reviews of the systems, readers are referred to Peng and Chiang (1984) and Singh (2015). Based on LTCC operation, several rock classification systems have been developed particularly for predicting top coal cavability, as reviewed in Le et al. (2017a). Among these systems, only the Top Coal Cavability Rating (TCCR) system (Vakili and Hebblewhite, 2010) is capable of assessing the first caving of top coal, or in other words, top coal stability.

4. SUMMARY AND CONCLUSIONS

This paper describes a systematic review of the roof instability mechanisms involved in LTCC mining and the applicability of conventional rock mass classification systems in assessing LTCC roof instabilities. The study confirms that in general the magnitude and location of peak abutment stress induced by LTCC are similar to those induced by conventional longwall mining. The predominant failure mode in roof rock mass can be either shear or tension while the driving failure mode in top coal is shear. The movement of immediate and main roofs in LTCC is similar to that in SPL while the movement of top coal can be divided into four different zones. The conventional rock mass classification systems whose databases were obtained from excavation/mining in sedimentary rocks/coal measure rocks can be applied in assessing LTCC roof stability. However, as these systems were mainly designed for a wide range of rock mass strength, their sensitivity to soft rocks such as coal may be low. This paper highlights the need for further understanding of LTCC-related strata behaviours (e.g., redistribution of horizontal stress) and the need for use of longwall development-based rock mass classification systems for better evaluating roof instability problems caused by LTCC. The paper's findings can assist engineers in better applying and managing LTCC operations.

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