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A new cavability assessment for Longwall Top Coal Caving from discontinuum numerical analysis

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ABSTRACT

This paper presents a new criterion for assessing top coal cavability in Longwall Top Coal Caving mining technology. Top coal Cavability Index (TCI) criterion was developed through a parametric study, statistical analysis and validation against field monitoring data. A discontinuum modelling technique with plastic rock material was used to quantify the impact of parameters on top coal cavability in a more realistic manner. The study demonstrated that an increase in the value of parameters such as immediate rock strength, coal strength, coal elastic modulus, coal vertical joint spacing, coal discontinuity friction angle and top coal thickness causes a decrease in top coal cavability, whereas an increase in the value of cover depth leads to an increase in the cavability. Coal elastic modulus was found to have a minor impact, while coal vertical joint spacing has the most significant impact on the cavability. The TCI criterion successfully incorporates the impacts of coal strength, rock strength and discontinuity friction angle into the evaluation of top coal cavability. The proposed criterion can thus be utilised to explicitly assess top coal cavability taking into account coal seam characteristics, surrounding rock mass properties and the nature of discontinuities, which contributes to improving reliability of the criterion.

1. Introduction

Longwall Top Coal Caving (LTCC) can provide substantially less economic sensitivity and a reduced level of technical risk over other thick seam mining methods.[1] A reliable evaluation of LTCC's applicability at the feasibility stage of a new mining project is therefore of importance to the effective and productive extraction of thick coal seams. The evaluation of LTCC's applicability technically refers to the assessment of top coal cavability. Top coal cavability is an inherent characteristic that indicates the sensitivity and possibility of top coal to cave under the action of front abutment stress.[2] An LTCC application is judged to be of low risk if top coal caves immediately after each advance of face support and in good fragmentation.[3] The application is of high risk if top coal caves far behind face support and is not recoverable, or if top coal caves immediately and excessively, which likely results in face instability and coal dilution. Top coal cavability thus largely contributes to the degree of success in LTCC operation.

A number of assessment criteria for top coal cavability have been developed and utilised in evaluating LTCC's applicability in practice. The criteria, however, have not sufficiently represented fundamental rock behaviours associated with LTCC mining such as intact rock failure, discontinuity failure and/or explicit rock caving, and this may result in assessment criteria with a restricted level of reliability. The analytical-based assessment criteria,[4,5] while incorporating intact coal failure for assessing cavability, give no direct consideration to discontinuity behaviour. This is probably due to the complexity in the analytical calculations when developing the criteria. The empirical-based criteria[2,6] are commonly derived from databases of past LTCC operations and they normally lack detailed consideration of rock mass mechanical behaviour. Although these criteria have been widely used in China because of its easy implementation and been successful in some cases, they should be applied with care to other coal mine sites outside the original databases.

Numerical-based criteria can provide a more rigorous and comprehensive assessment of top coal caving than analytical- and empirical-based criteria as they can represent complex geo-mining conditions. Depending on the modelling technique used, the criteria do not fully incorporate rock mass behaviours concomitant with LTCC mining, which restricts the reliability of cavability assessment. In particular, the criterion derived from continuum modelling technique[7] is typically limited in implicitly incorporating rock caving. This limitation is due to the continuum mechanics formulation of the code, which limits the

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simulation to small displacements and/or rotation.[8] The discontinuum modelling technique with plastic rock material is commonly associated with extremely complex rock mass response, which is attributed to the interaction between intact block failure and discontinuity failure.[9] The available discontinuum-based criteria[10,11] are therefore all derived from the modelling with elastic rock material that cannot capture intact rock failure. Additionally, the discontinuum-based criteria have not successfully taken into account the impact of roof strata movement on cavability. This was mainly due to the limited scale of LTCC face required to complete the modelling within acceptable time periods. A more detailed review of top coal cavability assessment is available in Le et al.[12]

This paper first presents a quantification of the impact of critical parameters related to roof strata characteristics, coal seam characteristics and pre-mining stress on top coal cavability in LTCC, which is performed by using a discontinuum modelling with plastic rock material. A new cavability assessment criterion is then developed through the implementations of statistical analysis of numerical modelling results and comparison with real LTCC performances. A corresponding cavability classification system is finally suggested and its validity is assessed using additional top coal caving performances at several mine sites in Australia and overseas.

2. Description of discontinuum modelling with plastic material

The Universal Distinct Element Code (UDEC)[8] was used to develop an LTCC model for the parametric study in this paper. This numerical program can efficiently model the critical features in LTCC operation such as periodic weighting of overburden strata and explicit caving of top coal and roof rock. Although UDEC has been widely used in studying coal/rock caving in longwall mining,[9,10,13–15] the previous modelling was limited in using elastic rock material as mentioned in Section 1. More recently, Le et al.[16] presented a field-scale UDEC model using plastic rock material. However, the model took approximately four months to complete the coal extraction simulation and thus could not be used practically for a detailed parametric study. Such modelling technique was adopted for developing the current LTCC model in a smaller scale, as described in the following paragraphs.

The model is developed based on one real LTCC face that was operated in a typical geo-mining condition at the Bowen Basin, Australia. The mine is named “Mine A” due to confidentiality matters. At Mine A, the coal seam has a depth at up to 300 m below surface and an average seam dip of three degrees.[17] The surrounding rock strata include three stratigraphic units that are coal, overbank and amalgamated distributary units.[18] Joints are most dense in coal seam and least dense in the distributary unit, with the predominant vertical joints set striking east-west ± 20°. The maximum horizontal stress predominantly orientates north-northeast and is on an average two times the vertical stress.[19] Although encountering some weighting events and cavity risks due to the presence of thick sandstones in roof strata, the LTCC operation was considered successful with a seam thickness recovery rate of up to 85%.[20]

The longwall face in the model is advanced along the panel length and located at the corresponding mid-panel width. The model represents 203 m of overburden strata, 7 m of coal seam and 40 m of floor thicknesses (Fig. 1). The total length of model is 600 m with the extraction length being 120 m in the centre. The model has nine major strata in which the areas of interest (coal seam, immediate roof, Main Roof 1 and Main Roof 2) were modelled with sufficient details of discontinuities. For instance, the spacing of discontinuities in coal seam was assigned 0.5 m based on the field observation of caved coal/rock sizes. The intact rocks in the areas of interest were simulated using strain-softening material and the discontinuities were modelled using the Coulomb slip model. The input material properties (Table 1) and simulations of face support and progressive mining were presented in detail in Le et al.[16] The model consists of 5298 blocks and takes around three weeks to complete the coal extraction simulation.

The model was calibrated against the field distance where top coal started to cave out of installation room, which was at 8–10 m of face advance. The model was then run further to validate against the field load on face support. This field load was derived from the Longwall Visual Analysis (LVA) data monitored in the first 120 m of the real mining.[16] The computed and field loads are displayed in Fig. 2, indicating good agreement in terms of load magnitude and trend. The top coal cavability in the model is measured through the Top Coal Recovery (TCR) rate[3] and shown in Eq. (1). For calculating TCR, the recovery is simulated by deleting any top coal blocks that cave into an area of 2.5 m length × 3.5 m height behind face support (a field recovery area). Although the TCR algorithm was proposed in Le et al.,[3] it was further tuned in this paper by assigning an explicit area for TCR calculation. This area is the interval between 30 and 120 m of face advance, where the caving should occur in its steady state. Using a FISH function (a built-in programming language available in UDEC),[8] TCR is automatically calculated and recorded after every face advance. After the full extraction (120 m of face advance), TCR reaches a rate of 85.57% which is very close to the seam recovery rate reported at the site.

$$TCR = \frac{\begin{array}{c} Total\ number\ of\ top\ \ coal\ blocks\ that\ have\ \ been\ recovered \\ (deleleted)\ \ to\ a\ current\ cut \end{array}}{Total\ number\ of\ pre-mining\ top\ coal\ blocks\ \ in\ the\ area\ of\ \ interest} \tag{1}$$

3. Parametric study of critical parameters

Identification and quantification of parameters that have significant impacts on top coal cavability are prerequisites for the development of a cavability assessment criterion. For the purpose of prediction, the criterion should include geotechnical parameters that can be simply collected at the feasibility stage of mine design. A critical review conducted by Le et al.[12] indicated that the key geotechnical parameters can be categorised into three groups—roof strata characteristics, coal seam characteristics and pre-mining stress. In roof strata characteristics, rock strength, bedding spacing and strata thickness control the movement of immediate and main roofs and therefore impact top coal cavability. The distance of face advance along panel length also contributes to the movement of roof strata[16] and it was carefully designed in the LTCC model. For coal seam characteristics, coal strength, which indicates coal's ability to resist failure, directly impacts the failure and hence the cavability of top coal. Coal elastic modulus governs the deformation of top coal section and hence influences top coal cavability. Discontinuities within coal seam are commonly high in frequency with low tensile strength; their geometric configuration and shear strength have an important role in top coal caving. Top coal thickness, which affects the quantity and quality of caving, is a decisive cavability factor. With regard to pre-mining stress, both vertical and horizontal stresses are redistributed during LTCC mining and result in rock mass failure. The stresses are considered to have significant impacts on cavability. Additionally, the relationship between face advance direction and major principal stress direction or pre-existing discontinuity orientation is believed to significantly affect the cavability. However, due to the two-dimensional nature of UDEC, it was not investigated in this paper.

The sensitivity of top coal cavability to a critical parameter was quantified on the basis of the LTCC model. It is noted that in this paper, as a common approach in sensitivity analysis, only the input value of an evaluated parameter is varied while the input values of other parameters are kept unchanged for all analyses. Also, coal and rock strength (Uniaxial Compressive Strength) and coal elastic modulus are scaled to their field-scale values, UCS^* and E^*, respectively.[16] All the input parameters for parametric study and the corresponding numerical values used for multiple regression analysis are listed in Table 2.

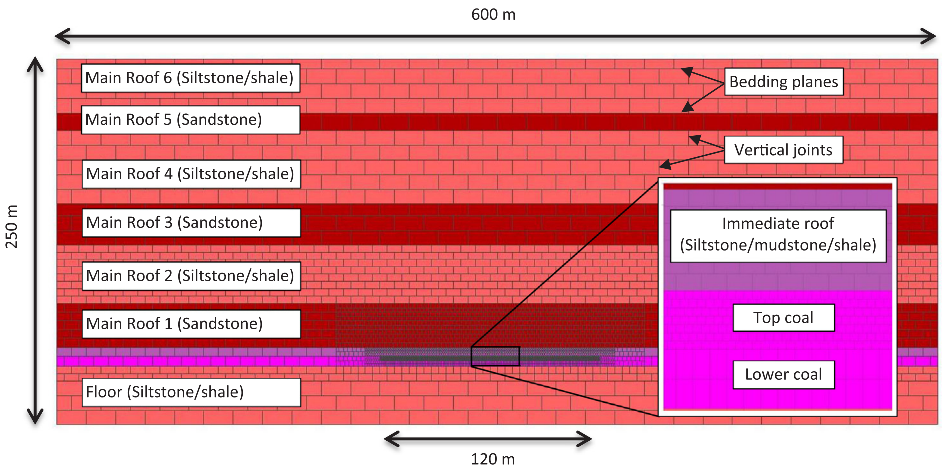

Fig. 1. Configuration of UDEC LTCC model.[3]

3.1. Roof rock strength

Four different strengths (*UCS**) of immediate rock were modelled to represent immediate roofs ranging from weak to strong strata. As the Mohr-Coulomb failure criterion was used in the models, the variation in rock strength was implemented by changing the cohesion or friction angle. The impact of immediate roof rock strength on top coal cavability is displayed in Fig. 3(a). It can be seen that the TCR value showed a decreasing trend when the immediate rock strength increased. This can be explained that as the rock strength increases, immediate roof can remain intact over a longer distance of face advance before starting to fail. The stronger immediate roof can delay the loads transferred from its own weight and from upper strata onto top coal. This decreased the degree of top coal failure and consequently reduced the TCR value. The result is in agreement with the numerical analysis conducted by Humphries et al.[7]

Four different strengths (*UCS**) of rock in Main Roof 1 were simulated to represent main roofs ranging from weak to strong strata, as shown in Table 3 and Fig. 3(b). It is seen that in the first case where the strata were weak, no voussoir beam could be formed[16] and the strata were easily broken (Fig. 4). In the last three cases where the strata were strong enough to form voussoir beams, when the rock strength increased, stronger Main Roof 1 formed more stable voussoir beams (longer face distance where strata started to rupture). The beams increasingly transferred the loads from Main Roof 1 and upper strata onto their abutments rather on the top coal ahead of coal face. Thus, the TCR values showed a decreasing trend in the three cases.

3.2. Coal strength

Five different strengths (*UCS**) of coal were modelled to represent seams ranging from weak to strong strata. As can be seen from Fig. 5, the TCR value decreased when the coal strength increased. The reason was that as the coal became stronger, it became more difficult to fail and therefore caused less TCR value. The impact of coal strength on its cavability in this study is in agreement with that from field experience.[2] A similar impact of coal strength was found by Humphries et al.,[7] where the plastic strain of top coal elements was measured as a cavability assessment.

3.3. Coal elastic modulus

Le et al.[3] modelled four different elastic moduli of coal and the associated TCR values are shown in Fig. 6(a). It can be seen that the TCR value followed a decreasing trend as the coal elastic modulus increased. This is because an increase in coal modulus increases the stiffness of top coal and can accordingly delay the caving of top coal. The impact of coal elastic modulus on coal cavability in this study agrees with past studies.[11,21] It should be noted that a stiffer coal seam has capacity to absorb more stress. While coal strength remains the same, the increased stress for a stiffer coal can increase the levels of top coal failure and cavability.

3.4. Coal discontinuity spacing

Previous study[3] shown in Fig. 6(b) illustrates that the TCR value significantly decreased when the vertical joint spacing increased. This result agrees well with Vakili and Hebblewhite[10] in that the density of vertical joints largely controls the shear strength of coal layers in vertical direction. Larger vertical joint spacing increases the overall strength of top coal section and thus causes less cavability.

For the analysis of bedding spacing's impact on cavability, only three different bedding spacings within top coal were modelled in Le et al.[3] due to the limited thickness of top coal (3.5 m). It is shown from Fig. 6(c) that the TCR value followed an increasing trend with an increase in the bedding spacing. This result seems to be counter-intuitive as greater bedding spacing means lower discontinuity density. Field observations regarding the impact of bedding spacing on top coal cavability, unfortunately, are currently unavailable.

The increasing trend of TCR in Fig. 6(c) might be possibly explained as shown in Fig. 7. The figure illustrates the state of a red square top coal block in the initial extraction where top coal has not caved yet. The block is in equilibrium because the driving force ($F + P$), which induces the block to cave, is less in magnitude than the resistant force (R), which resists the block to move. Here, the driving force includes the self-weight force (F) and load from overburden rock (P). They can be easily calculated based on block dimensions, gravity acceleration, depth of cover, and densities of coal and overburden. Meanwhile, the resistant force is mainly generated by the joint shear strength on the two vertical sides of the block and the clamping force. The clamping force acting on the two sides is the horizontal stress, which can be derived from the cover depth, overburden density, gravity acceleration and a horizontal-to-vertical stress ratio. In the subsequent extraction where top coal can cave cyclically (normal caving cycles), the horizontal stress acting on a potential caving block is significantly released because of previous mining. At the same time, the potential caving block is resisted by the joint shear strength on one side as the other side is goaf boundary. The resistant force therefore significantly decreases, and the weight force of the block now plays a significant role in its caving. A stringent explanation on the current numerical analysis result, however, has been recognised as a focus of further study.

Table 1
Coal and rock properties used in UDEC LTCC model.[16]

Rock unit	Block properties								Discontinuity properties				
	Field Uniaxial Compressive Strength (MPa)	Field elastic modulus (GPa)	Friction (°)	Cohesion (MPa)	Tensile strength (MPa)	Residual cohesion (MPa)	Residual tensile strength (MPa)	Critical strain (%)	Normal stiffness (GPa/m)	Shear stiffness (GPa/m)	Cohesion (MPa)	Friction (°)	Tensile strength (MPa)
Sandstone	26.62	8.25	42	5.92	2.66	1.18	0.26	0.1	100	10	0	25	0
Siltstone/shale	17.40	5.39	34	4.62	1.74	0.92	0.17	0.1	100	10	0	25	0
Siltstone/shale/mudstone	11.60	3.59	34	3.08	1.16	0.61	0.11	0.1	100	10	0	20	0
Coal	6.64	2.05	30	1.91	0.66	0.38	0.06	0.5	100	10	0	15	0

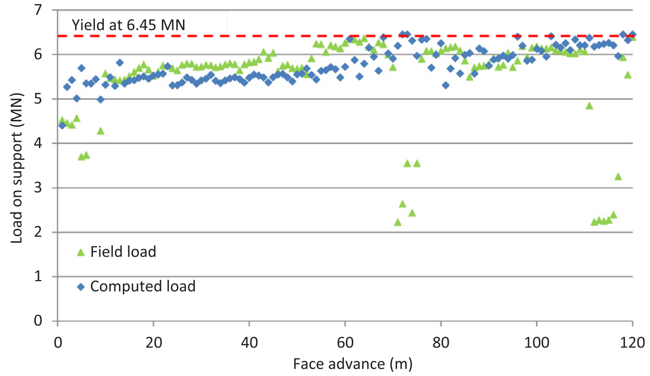

Fig. 2. Computed and field loads on face support for a 120 m coal extraction model.

3.5. Coal discontinuity strength

Based on empirical observations, Mahtab and Dixon[22] stated that the strength of discontinuities is one of the key parameters impacting cavability and that favourably inclined, closely spaced discontinuities with low resistance to in-plane shear stress facilitate caving. In the current study, four possible friction angles of discontinuities within coal seam were modelled. The tensile strength and cohesion of the discontinuities were assumed to be zero. As can be seen from Fig. 8(a), the TCR value showed a decreasing trend when the friction angle increased. The result denotes that within a thick coal seam, stronger discontinuities reduce top coal cavability and vice versa, which is in accordance with the observation mentioned earlier. It is noted that in the four models, the vertical joints and bedding planes were assumed to have the same strength. As top coal mainly failed and caved along the vertical joints, the assumption did not significantly impact the above result.

3.6. Top coal thickness

As presented in Le et al.,[3] an increase in top coal thickness resulted in a decrease in the TCR value (Fig. 8(b)). One main reason was that a thicker top coal required a larger void space to rotate and cave. As the cutting height was the same between the four models, TCR thus decreased when the thickness increased. The result corresponds well with Vakili and Hebblewhite.[10]

3.7. Pre-mining stress

In the current work, five different depths of cover were modelled and the ratio of horizontal to vertical stress was kept constant throughout the models. The TCR value, as seen in Fig. 8(c), followed an increasing trend with an increase in the cover depth. The trend can be explained by the fact that greater depth resulted in greater front abutment stress. The increased stress facilitated top coal failure and subsequently increased the TCR value.

The impact of horizontal stress along the panel length on top coal cavability has also been investigated. It is believed that this stress is significantly released due to the formations of goaf area and re-distributed around caving areas. The abutment stress thus becomes major principal stress while the horizontal stress in the direction of face advance becomes minor principal stress. The release of the horizontal stress, due to stress rotation and redistribution as shown in the study,[5] would drastically decrease the bearing capacity of top coal ahead of the LTCC face and play an important role in top coal caving.

Table 2
Input parameters and numerical values used for multiple regression analysis.

Order	Field strength of immediate rock (MPa)	Field strength of coal (MPa)	Field elastic modulus of coal (GPa)	Spacing of vertical joints within coal (m)	Friction angle of discontinuities within coal (°)	Top coal thickness (m)	Depth of cover (m)	TCR (%)
1	11.6	6.64	2.05	0.5	15	3.5	210	85.57
2	7.73	6.64	2.05	0.5	15	3.5	210	87.79
3	17.4	6.64	2.05	0.5	15	3.5	210	83.91
4	26.1	6.64	2.05	0.5	15	3.5	210	80.97
5	11.6	2.95	2.05	0.5	15	3.5	400	88.50
6	11.6	4.43	2.05	0.5	15	3.5	400	85.65
7	11.6	6.64	2.05	0.5	15	3.5	400	83.35
8	11.6	9.96	2.05	0.5	15	3.5	400	82.48
9	11.6	14.94	2.05	0.5	15	3.5	400	80.74
10	11.6	6.64	1.37	0.5	15	3.5	210	85.89
11	11.6	6.64	3.08	0.5	15	3.5	210	85.09
12	11.6	6.64	4.63	0.5	15	3.5	210	80.73
13	11.6	6.64	2.05	0.75	15	3.5	210	66.93
14	11.6	6.64	2.05	1	15	3.5	210	48.35
15	11.6	6.64	2.05	1.25	15	3.5	210	41.90
16	11.6	6.64	2.05	0.5	10	3.5	210	86.12
17	11.6	6.64	2.05	0.5	22.5	3.5	210	83.51
18	11.6	6.64	2.05	0.5	33.75	3.5	210	77.01
19	11.6	6.64	2.05	0.5	15	1.5	210	93.03
20	11.6	6.64	2.05	0.5	15	2.5	210	89.75
21	11.6	6.64	2.05	0.5	15	4.5	210	78.81
22	11.6	6.64	2.05	1	15	3.5	300	59.16
23	11.6	6.64	2.05	1	15	3.5	400	57.90
24	11.6	6.64	2.05	1	15	3.5	500	60.27
25	11.6	6.64	2.05	1	15	3.5	600	62.96
26	11.6	6.64	2.05	1	15	3.5	700	63.44

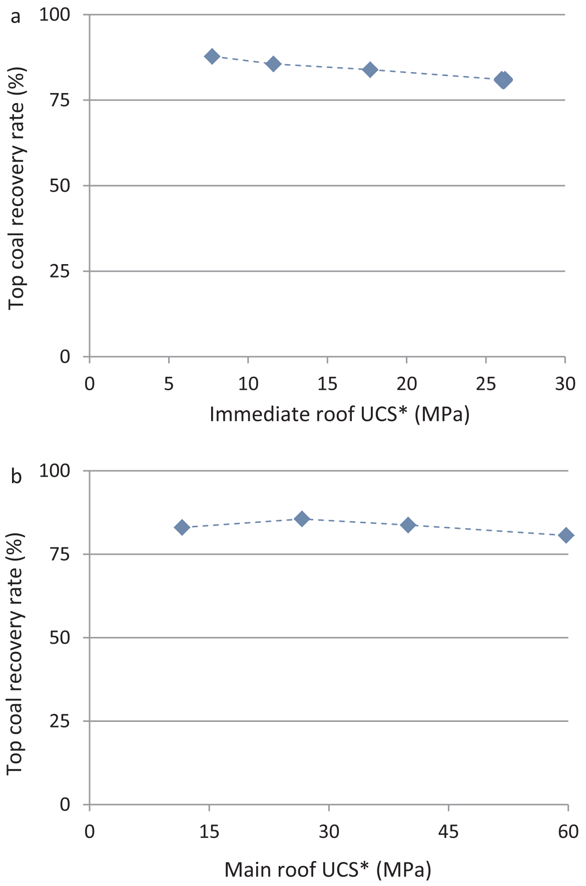

Fig. 3. Impacts of (a) immediate roof rock strength and (b) main roof rock strength on TCR.

Table 3
UDEC analysis of main roof rock strength.

UCS* (MPa)	Face distance where main roof caving/weighting first occurs (m)	TCR (%)
11.60	43	83.0
26.62	73	85.6
39.93	75	83.8
59.74	75	80.7

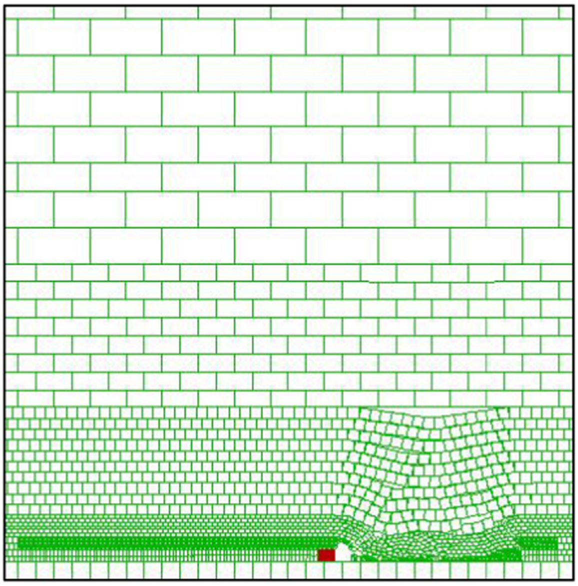

Fig. 4. Caving in weak main roof strata.

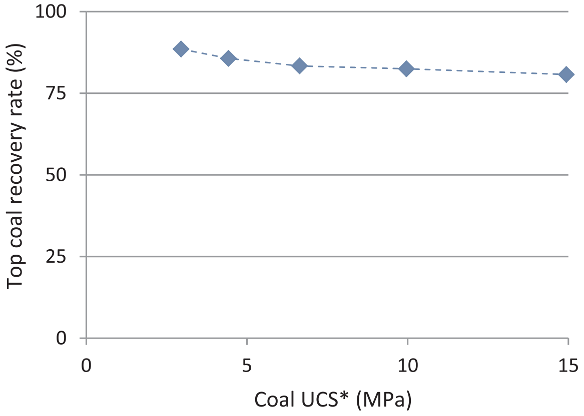

Fig. 5. Impact of coal strength on TCR.

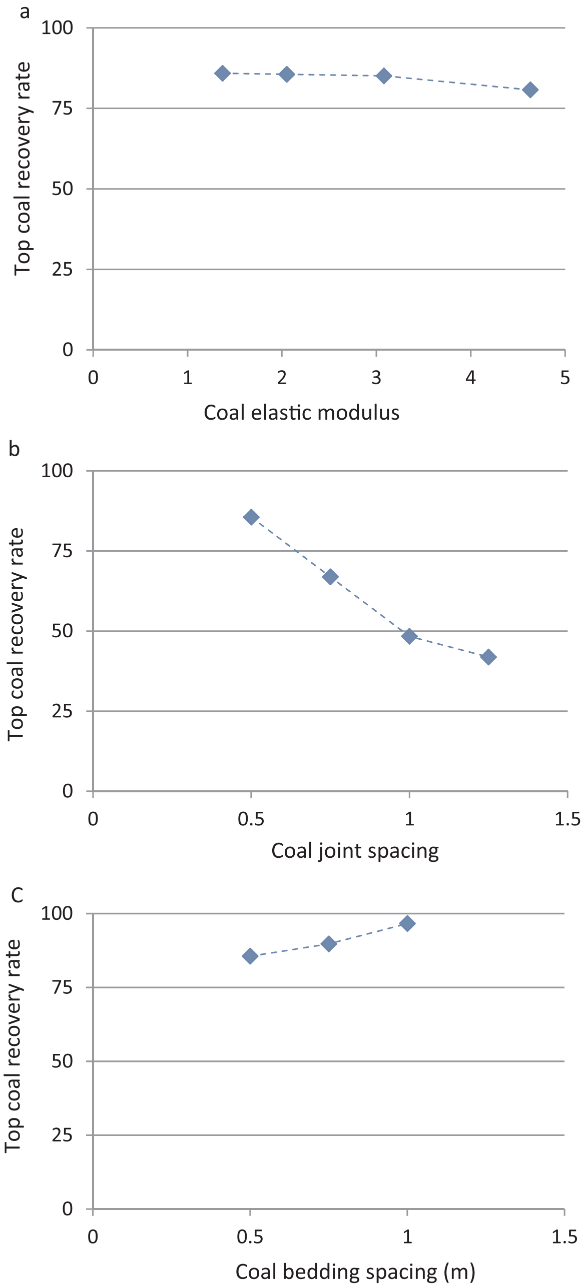

Fig. 6. Impacts of (a) coal elastic modulus, (b) coal vertical joint spacing and (c) coal bedding spacing on TCR.[3]

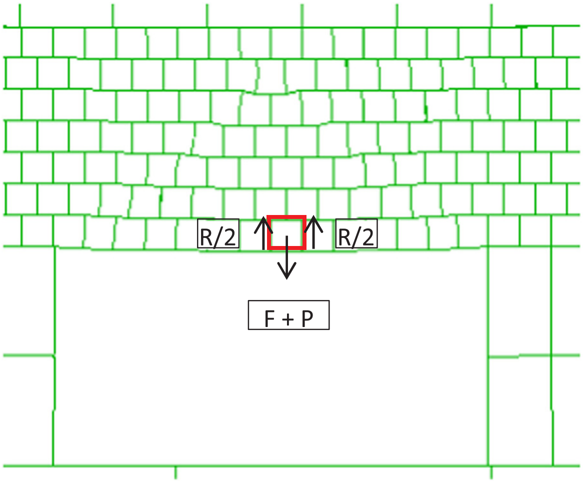

Fig. 7. Top coal block in initial extraction.

4. New assessment criterion for top coal cavability

4.1. Statistical analysis

A multiple regression analysis was carried out to develop a predictive equation for top coal cavability (dependent variable) from multiple critical parameters (independent variables). From the parametric study, only seven parameters (i.e., immediate roof rock strength, coal strength, coal elastic modulus, coal vertical joint spacing, coal discontinuity strength, top coal thickness and depth of cover) were proposed for the multiple regression, where impacts on top coal cavability can be generalised and are mechanistically explainable. As these impacts appeared to be linear, a multiple linear regression, which should form a simplified equation readily applicable in the feasibility stage of mine design, was considered the best fit model for the analysis. The regression outputs (Tables A.1 and A.2) indicates that every independent parameter actually impacts the cavability with reasonable correlation; the validity of the regression model is confirmed with strong evidence; and most of the parameters are significant at a 0.05 Level of Significance. The regression formed the following equation

$$TCI = 140.89 - 0.225IMR^{*} - 0.693UCS^{*} - 1.028E^{*} - 57.568JS - 0.333DF - 4.85TC + 0.015D \tag{2}$$

where *TCI* is the Top coal Cavability Index (%); *IMR** is the field uniaxial compressive strength of immediate roof rock (MPa); *UCS** is the field uniaxial compressive strength of coal (MPa); *E** is the field elastic modulus of coal (GPa); *JS* is the spacing of vertical joints within coal seam (m); *DF* is the friction angle of discontinuities within coal seam (°); *TC* is the top coal thickness (m); and *D* is the cover depth of coal seam (m).

The parameters in Eq. (2) have different units and therefore their coefficients cannot be used in comparing their relative impacts on top coal cavability. Standardised Multiple Regression method, which helps to control round-off errors in normal calculations and to permit comparisons of the estimated coefficients in common units,[23] was applied to analyse the importance of individual parameters. The analysis from Tables A.3 and A.4 shows that in terms of statistics coal elastic modulus has a minor impact while coal vertical joint spacing has the most significant impact on top coal cavability. It is important to note that in cases where coal seams are less fractured or intact, intact coal characteristics should play a more important role in the cavability.

4.2. Top coal Cavability Index (TCI) criterion

Eq. (2) can serve as an assessment criterion for top coal cavability

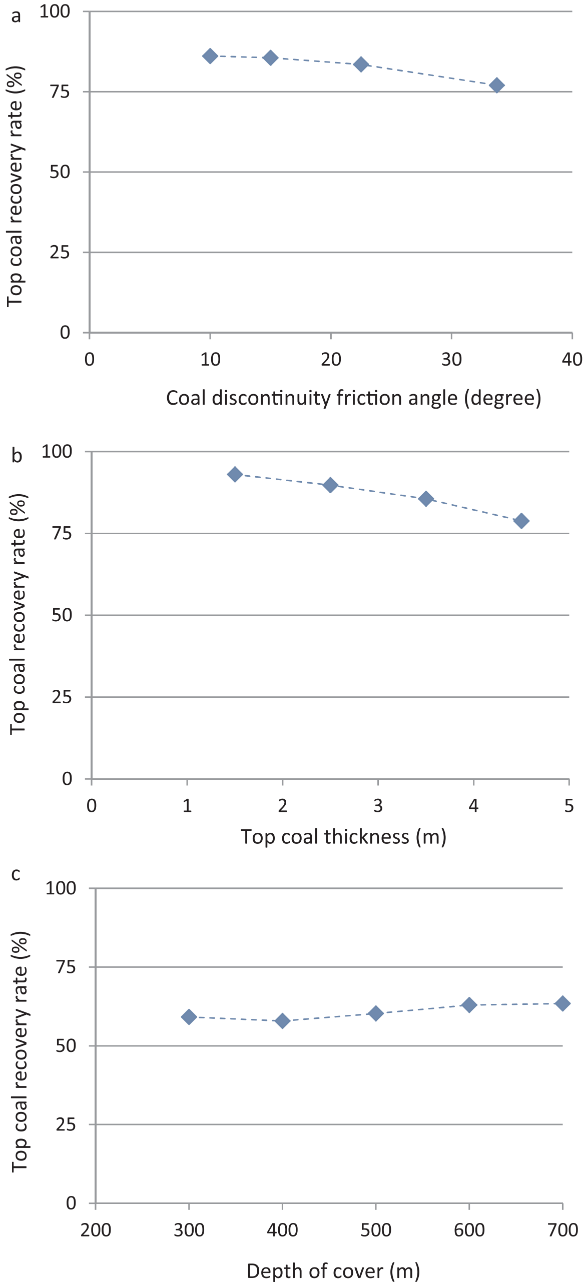

Fig. 8. Impacts of (a) coal discontinuity friction, (b) top coal thickness[3] and (c) depth of cover on TCR.

and is called the Top coal Cavability Index (TCI) criterion. The reliability of the TCI criterion was assessed using the geotechnical parameters and corresponding caving performances at two sets of real LTCC faces.[6,7] For this TCI calculation, a few assumptions were made to evaluate the values of material properties as follows: (1) the field strength of coal and rock were scaled from the available intact uniaxial compressive strength using a reduction factor of 0.58, which was used in the model development.[16] Note that various methods for scaling rock strength from laboratory to field scale can be found in many studies[24–28]; (2) the immediate rock strength was assumed to be double the coal strength. This assumption was based on the representative strengths of typical coal measure rocks[29] and it may not correctly capture the rock strength variation in reality; (3) the coal elastic modulus in GPa was roughly estimated to be 0.3 times the coal strength in MPa, which is based on general empirical relationships between them in past studies[24,25]; and (4) the friction of discontinuities was assumed to be at 15° for all faces. Of note is that these assumptions were made due to the lack of data at those longwall faces which may reduce the accuracy of the calculation.

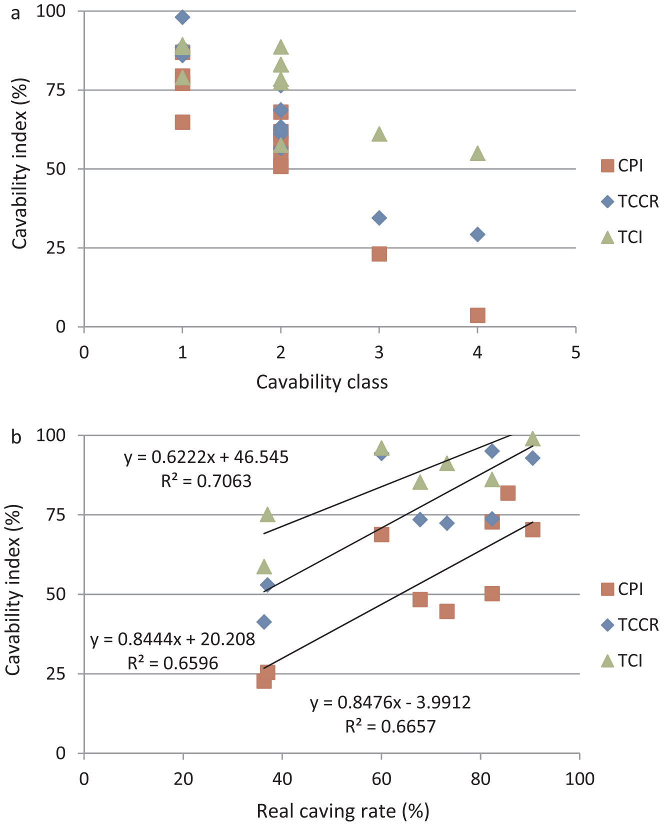

Fig. 9. Comparisons between TCI, TCCR, CPI predictions with (a) the cavability class in Jia.[6] and (b) the real recovery rate in Humphries et al.[7]

The calculated TCI result was then compared to the field caving indices, as illustrated in Fig. 9(a) and (b). These two figures also display the calculated results from other numerical-based criteria such as Top Coal Cavability Rating (TCCR)[10] and Caving Performance Index (CPI),[11] for the purpose of comparing the criteria's reliability. Fig. 9(a) shows that the predicted TCI, TCCR and CPI values have similar relationships with the cavability classes proposed by Jia.[6] It should be noted that the Jia's classification is recommended for a preliminary assessment only because no realistic caving index (e.g., recovery rate) was presented in the Jia's original data. Alternatively, Fig. 9(b) shows that the predicted TCI value, compared to the predicted TCCR and CPI values, has the greatest correlation with the real recovery rate reported in Humphries et al.,[7] which proves that the TCI prediction is more reliable than those of TCCR and CPI.

The four TCI classes was suggested based on the TCI criterion as well as past cavability classification systems,[2,5–7,10,11] taking into consideration the requirements related to coal recovery rate in LTCC face in China[1] and Vietnam.[30] in Table 4. The validity of the TCI system was assessed using additional caving performances from four LTCC faces in different countries, as presented in Table 5. The differences between predicted TCI values and real recovery rates were all less than 12%, confirming the validity of the proposed system. It should be noted that the use of TCI outside its original database, as similar to empirical criteria, is not recommended.

5. Discussion and conclusions

The proposed TCI criterion provides a predictive tool for assessing top coal cavability with more reliable results compared to other criteria.

Table 4
Cavability classification in TCI system.

Class	TCI (%)	Description
1	> 90	*Excellent cavability* Top coal immediately caves after advance of face support. Top coal recovery rate is predicted to be at its maximum with good fragmentation. Face and roof instabilities may occur due to excessive top coal caving.
2	80–90	*Good cavability* Top coal caves with little delay after advance of face support. Top coal recovery rate is less than that in Class 1 with larger fragmentation. Face and roof instabilities are less significant than those occurring in Class 1.
3	70–80	*Medium cavability* Top coal caves with delays after advance of face support. Top coal recovery rate is predicted to be average with poor fragmentation. Immediate roof is stronger and that reduces the risk of roof instabilities.
4	< 70	*Poor cavability* Strong top coal hangs up and caves far behind face support. Top coal recovery rate is predicted to be at its minimum with large block size. Strong immediate roof reduces top coal cavability.

Table 5
Cavability assessment in different countries using TCI system.

Parameter	Austar, Australia	Xinglongzhuang, China	Nammau, Vietnam	Halam, Vietnam
IMR (MPa)	40	57	45.6	56.8
UCS (MPa)	17.5	25	25	22.5
JS (m)	0.25	0.35	0.15	0.15
DF (°)	15	15	15	15
TC (m)	4.4	5.1	3.9	5.4
D (m)	460	429	150	300
TCI (%)	91.5	75.3	89.9	85
Real rate (%)	85	79	80.6	88
TCI class	1—Excellent	3—Medium	2—Good	2—Good

The advantage of TCI is attributable to the sufficient dimension of face advance along panel length in the evaluation of key parameters impacting top coal cavability. In past criteria derived from discontinuum modelling,[10,11] the length of face advance was limited to no more than 50 m that could not result in distinct downward movement of roof strata. In the current criterion, the modelled length was 120 m that enabled the first and second ruptures of main roof strata occurred. In other words, the periodic weighting of roof strata occurred in most of the models. This means that the impacts of parameters on top coal cavability were quantified in normal caving cycles and under the distinct impact of roof strata movement.[16] The significance of individual parameters on the overall cavability in TCI has been reliably obtained, and this subsequently results in more reliable TCI prediction.

The advantage of TCI over other criteria is also attributed to the successful use of plastic rock material with strain softening behaviour when assessing the influence of parameters on cavability. In particular, the LTCC models used in the study not only explicitly represented the caving of top coal/rock but also adequately captured the intact rock failure and rock strength disintegration. With these fundamental rock responses, the impacts of parameters on cavability were realistically quantified. This contributes to more reliable TCI assessment. Furthermore, due to the use of plastic rock material in simulations, the strength of coal and immediate roof rock, which has not been considered in other discontinuum-based criteria, has been explicitly incorporated into TCI. The discontinuity friction angle is another new parameter that has been added into TCI, taking into account the impact of discontinuity strength on top coal cavability.

This paper presents a new assessment criterion for top coal cavability in LTCC. The impact of critical parameters on cavability has been realistically quantified by using a discontinuum modelling with plastic rock material. The study provides further numerical evidences to confirm that an increase in the value of immediate roof rock strength, coal strength, coal elastic modulus, coal vertical joint spacing, coal discontinuity friction angle and top coal thickness causes less cavability, whereas an increase in the value of cover depth results in more cavability. Coal elastic modulus is found to have a minor impact while coal vertical joint spacing has the most significant impact on cavability. The TCI criterion successfully incorporates the impacts of immediate roof rock strength, coal strength, coal elastic modulus, coal vertical joint spacing, coal discontinuity friction angle, top coal thickness and cover depth for a more reliable top coal cavability assessment. The proposed TCI criterion can be utilised when evaluating LTCC's applicability for a new mine site.

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Appendix A

The multiple linear regression model in Section 4 is given as:

Table A.1
Regression statistics.

Parameter	Value
Multiple R	0.987561061
R Square	0.975276849
Adjusted R Square	0.96566229
Standard Error	2.548967464
Observations	26

Table A.2
Analysis Of Variance (ANOVA).

	Degree of freedom	Sum Squares	Mean Squares	F	Significance F
Regression	7	4613.4432	659.0633	101.4375	3.70162E − 13
Residual	18	116.9502	6.497235		
Total	25	4730.3934			

Table A.3
Transformed variables for standardised multiple regression analysis.

Order	Field strength of immediate rock	Field strength of coal	Field elastic modulus of coal	Spacing of vertical joints within coal	Friction angle of discontinuities within coal	Top coal thickness	Depth of cover	TCR
1	−0.0401	−0.0223	−0.0402	−0.1252	−0.0401	0.0318	−0.1333	0.1370
2	−0.2855	−0.0223	−0.0402	−0.1252	−0.0401	0.0318	−0.1333	0.1693
3	0.3279	−0.0223	−0.0402	−0.1252	−0.0401	0.0318	−0.1333	0.1128
4	0.8798	−0.0223	−0.0402	−0.1252	−0.0401	0.0318	−0.1333	0.0702
5	−0.0401	−0.3965	−0.0402	−0.1252	−0.0401	0.0318	0.1411	0.1796
6	−0.0401	−0.2471	−0.0402	−0.1252	−0.0401	0.0318	0.1411	0.1382
7	−0.0401	−0.0223	−0.0402	−0.1252	−0.0401	0.0318	0.1411	0.1047
8	−0.0401	0.3148	−0.0402	−0.1252	−0.0401	0.0318	0.1411	0.0921
9	−0.0401	0.8196	−0.0402	−0.1252	−0.0401	0.0318	0.1411	0.0667
10	−0.0401	−0.0223	−0.2829	−0.1252	−0.0401	0.0318	−0.1333	0.1416
11	−0.0401	−0.0223	0.3274	−0.1252	−0.0401	0.0318	−0.1333	0.1301
12	−0.0401	−0.0223	0.8806	−0.1252	−0.0401	0.0318	−0.1333	0.0667
13	−0.0401	−0.0223	−0.0402	0.0783	−0.0401	0.0318	−0.1333	−0.1340
14	−0.0401	−0.0223	−0.0402	0.2817	−0.0401	0.0318	−0.1333	−0.4041
15	−0.0401	−0.0223	−0.0402	0.4852	−0.0401	0.0318	−0.1333	−0.4980
16	−0.0401	−0.0223	−0.0402	−0.1252	−0.2854	0.0318	−0.1333	0.1451
17	−0.0401	−0.0223	−0.0402	−0.1252	0.3279	0.0318	−0.1333	0.1070
18	−0.0401	−0.0223	−0.0402	−0.1252	0.8798	0.0318	−0.1333	0.0126
19	−0.0401	−0.0223	−0.0402	−0.1252	−0.0401	−0.7954	−0.1333	0.2454
20	−0.0401	−0.0223	−0.0402	−0.1252	−0.0401	−0.3818	−0.1333	0.1977
21	−0.0401	−0.0223	−0.0402	−0.1252	−0.0401	0.4454	−0.1333	0.0388
22	−0.0401	−0.0223	−0.0402	0.2817	−0.0401	0.0318	−0.0033	−0.2469
23	−0.0401	−0.0223	−0.0402	0.2817	−0.0401	0.0318	0.1411	−0.2653
24	−0.0401	−0.0223	−0.0402	0.2817	−0.0401	0.0318	0.2855	−0.2308
25	−0.0401	−0.0223	−0.0402	0.2817	−0.0401	0.0318	0.4299	−0.1917
26	−0.0401	−0.0223	−0.0402	0.2817	−0.0401	0.0318	0.5743	−0.1848

Table A.4
Coefficients from standardised multiple regression analysis.

	Coefficients	Standard Error	t Stat	p-value	Lower 95%	Upper 95%
Intercept	−7.5E − 17	0.0073	−1. E − 14	1.0000	−0.0153	0.0153
Field strength of immediate rock	−0.0515	0.0378	−1.3603	0.1905	−0.1309	0.0280
Field strength of coal	−0.0993	0.0375	−2.6488	0.0163	−0.1781	−0.0205
Field elastic modulus of coal	−0.0419	0.0378	−1.1064	0.2831	−0.1213	0.0376
Spacing of vertical joints within coal	−1.0284	0.0417	−24.6555	2.5E − 15	−1.1160	−0.9408
Friction angle of coal discontinuities	−0.0987	0.0378	−2.6078	0.0178	−0.1781	−0.0192
Top coal thickness	−0.1705	0.0376	−4.5387	0.0003	−0.2494	−0.0916
Cover depth of coal seam	0.1495	0.0419	3.5708	0.0022	0.0615	0.2374

$$TCI = b_0 + b_1 IMR^* + b_2 UCS^* + b_3 E^* + b_4 JS + b_5 DF + b_6 TC + b_7 D \tag{A.1}$$

where TCI is the Top coal Cavability Index (%); IMR^* is the field uniaxial compressive strength of immediate roof rock (MPa); UCS^* is the field uniaxial compressive strength of coal (MPa); E^* is the field elastic modulus of coal (GPa); JS is the spacing of vertical joints within coal seam (m); DF is the friction angle of discontinuities within coal seam (°); TC is the top coal thickness (m); D is the cover depth of coal seam (m); and b_1, b_2, b_3, b_4, b_5, b_6, b_7 are the coefficients of independent variables. Statistics and Analysis Of Variance from this regression are shown in Tables A.1 and A.2.

As stated in Section 4, Standardised Multiple Regression is a method that helps to control round-off errors in normal calculations and to permit comparisons of the estimated regression coefficients in common units.[23] Correlation Transformation is a simple modification of the usual standardisation of a variable. Standardising a variable involves centring and scaling the variable. Centring means taking the difference between each observation and the mean of all observations for the variable. Scaling means expressing the centred observations in units of the standard deviation of the observations for the variable. The transformed variables of a dependent variable Y_i and an independent variable X_{ik} are as follows:

$$Y_i' = \frac{1}{\sqrt{n-1}}\left(\frac{Y_i - \bar{Y}}{s_Y}\right) \tag{A.2}$$

$$s_Y = \sqrt{\frac{\sum (Y_i - \bar{Y})^2}{n-1}} \tag{A.3}$$

where $\bar{Y}$ is the mean value; s_Y is the standard deviation; and n is the number of observations.

$$X'_{ik} = \frac{1}{\sqrt{n-1}}\left(\frac{X_{ik} - \bar{X}_k}{s_k}\right) \tag{A.4}$$

$$s_k = \sqrt{\frac{\sum (X_{ik} - \bar{X_k})^2}{n-1}} \tag{A.5}$$

where $\bar{X}$ is sample mean for the independent variable k (k ranges from 1 to the number of independent variables); s_k the standard deviation; and n is the number of observations.

The standardised multiple regression model of Eq. (A.1) is as follows:

$$TCI' = b'_1 IMR^{*\prime} + b'_2 UCS^{*\prime} + b'_3 E^{*\prime} + b'_4 JS' + b'_5 DF' + b'_6 TC' + b'_7 D' \tag{A.6}$$

The transformed variables used for and coefficients obtained from this standardised regression analysis are presented in Tables A.3 and A.4.

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