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Xuan-Nam Bui
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Analytical Study on the Stability of Longwall Top Coal Caving Face

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Abstract. Longwall face instability is a critical geotechnical issue in the operation of longwall with considerable mining height and significant caving height. Of the commonly applied research techniques, analytical solutions can provide fundamental insight into key mechanics of face stability to decide if the more in-depth but costly analysis is to be implemented. The paper first presents a mechanical model of face spall in mechanized longwall top coal caving method in which the interaction between coal seam, shield support and roof strata is taken into consideration. An equation for estimation of face spall extent is then developed from the model, using field observations at two typical mechanized longwall top coal caving faces at Quang Ninh coalfield, Vietnam. The estimation demonstrates that the equation is applicable to the cases where the spall is mainly caused by the ruptures of the immediate roof and top coal beams. When the main roof ruptures, the roof pressure is rapidly increased that may cause shield damage and whole face collapse. The paper's results provide mining engineers with a low-cost tool for quick evaluation of face instability risk in the preliminary stage of mine design.

Keywords: Face stability · Spall extent · Mechanical model · Field observation

1 Introduction

Face instability is always a critical geotechnical issue in the operation of longwall coal mining, especially when applying modern technologies such as extra cutting height and/or caving height. The issue may occur in small (spall or slab in centimeters) to a large extent (spall or fall in meters) that threatens worker's safety, damages expensive equipment, and interrupt normal production. For example, a large face spall occurred at Seam 11 Ha Lam coal mine in Quarter III 2019 caused the face stopped in about two weeks, resulting in an economic loss of 140,000 USD per day. In order to control the problem, face stability mechanics and their driving parameters have been extensively studied for many years through various research techniques, such as field measurement, analytical solution, computational modeling, and physical modeling. Field measurement [1, 2] and physical modeling [3] studies can provide fundamental insight into instability mechanisms. However, they should be carefully performed due to high costs and

long design time. Computational modeling studies [4, 5], in contrast, can reveal micro-mechanisms of the instability at reasonable cost and time. To achieve reliable outputs, they require good modeling strategy and sound justification for many unknown input parameters. For cases where a fundamental insight into crucial mechanics of face stability is needed to decide if the more in-depth and but costly analysis is to be implemented, an analytical solution should be first considered as the main study tool. Although the solution requires simplifications of rock mass conditions and failure criterion, it can produce, satisfactory outcomes if a simplified mechanical model is adequately developed, and calculation inputs are reliably estimated. Analytical solution, as typically restricted to two-dimensional problems due to complexity, is well suited to analyzing longwall face-associated geomechanics since the face is long in strike direction and continuous in dip direction [6].

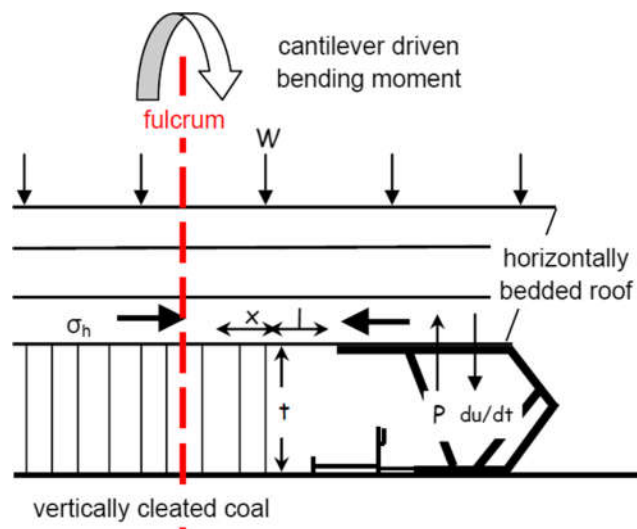


Fig. 1. Conceptual model of longwall face stability [7]. W is abutment loading; t is extraction height; l is tip to face distance; x is faced spall depth; σ_h is horizontal stress; du/dt is the rate of shield convergence; P is shield loading.

A number of mechanical models of longwall face stability were developed in previous analytical studies. Frith [7] proposed a conceptual model that was composed of a vertically cleated coal seam, a horizontally bedded immediate roof loaded by overburden strata, and shield support (Fig. 1). Based on the theory of Euler buckling (in particular, critical buckling stress/load in a vertical column), the face spall depth x was found as a function of abutment stress σ_v and cutting height t . Similarly, the roof fall potential ahead of shield support was controlled by the mining-induced horizontal stress σ_h and unsupported span $l + x$ between shield and face line. Wang, Yang, and Kong [8], based on practical observation of shear spall incidents, presented a shear failure model of a single pass longwall face (Fig. 2). Using the limit equilibrium method and Mohr-Coulomb strength theory, the authors assessed the face stability condition through a safety index, which was the ratio of shear stress to shear strength applied on the coal spalling block. The involved parameters were roof load, the gravity of spalling block, shield guard force, coal seam strength parameters, and heights of cutting and spalling coal. The index was further improved in Kong, Cheng, and Zheng [9] in which the friction f between coal

body and the immediate roof was taken into consideration, as shown in Fig. 3. It is also seen that the ruptured main roof was explicitly incorporated into the analysis in the figure.

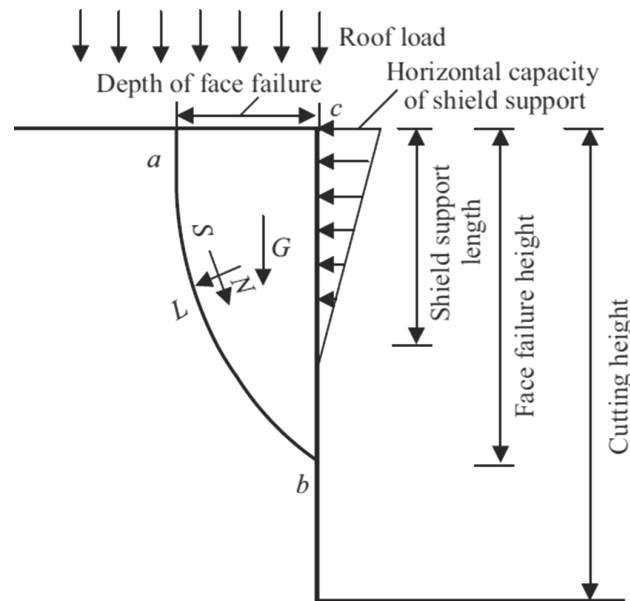


Fig. 2. Shear failure model of face spall in single pass longwall [8]. a , b and c are corners of failure block; G is the weight of failure block; L is the length of failure plane, and S is shear strength.

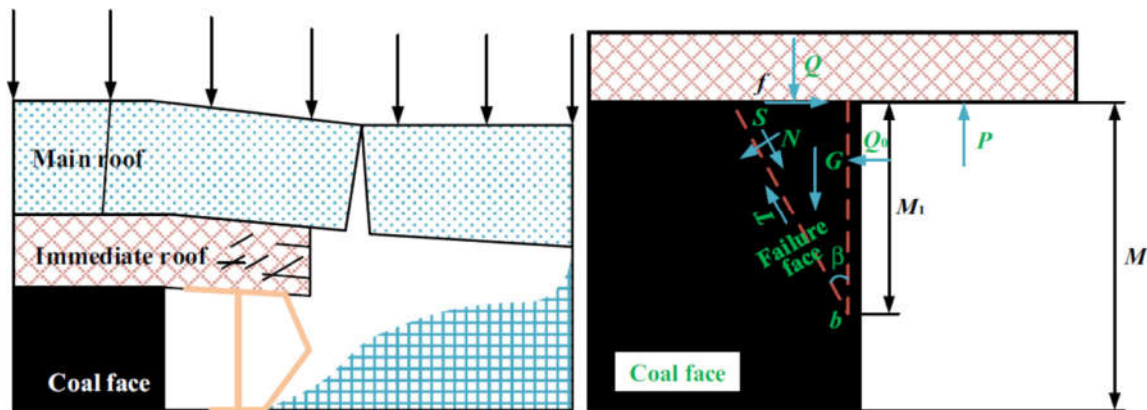


Fig. 3. System of the face-support-roof (left) and its simplification (right) [9]. Q is overlying strata pressure; Q_o is acting force on face; P is shield resistance force; G is the gravity of sliding body; S and N are shear and regular forces on sliding surface; T is the shear force on failure face; f is friction between coal and roof, and β is failure angle.

Another approach in the analytical solution for face stability is to consider the equilibrium of face-support-roof system in terms of energy or moment. For longwall top, coal caving (LTCC) face, Wang and Wang [10] applied energy conservation principle to transform the kinetic energy of broken rock block into intact coal, broken top coal and face support in the form of dynamic load, plus surface energy and heat energy of fractures (Fig. 4a–b). The theory of elastic foundation beam was then used to calculate

the roof pressure acting on coal wall and shield support. This pressure was finally compared to the strength of both coal wall and shield support to assess the system's stability. For single-pass large longwall mining (SPLL), the approach was similar, but no energy transformation was considered due to the absence of the top coal section (Fig. 4c–d). In both cases, strength and stiffness of coal seam, as well as stiffnesses of roof strata and shield support, were found as key driving factors of face stability. The energy conservation principle was also applied by Guo, Liu, Dong, and Lv [11] for single-pass longwall in where the main roof formed a voussoir beam (Fig. 5a). The authors stated that the work done by rotation of primary and immediate roofs must be equal to the deformation energy stored in the immediate roof, coal wall, and shield support. The authors added another model in where the main roof formed cantilever beam (Fig. 5b). In both models, at the instant when the main roof ruptured, the sum of moments of the system about rotating point O should be zero.

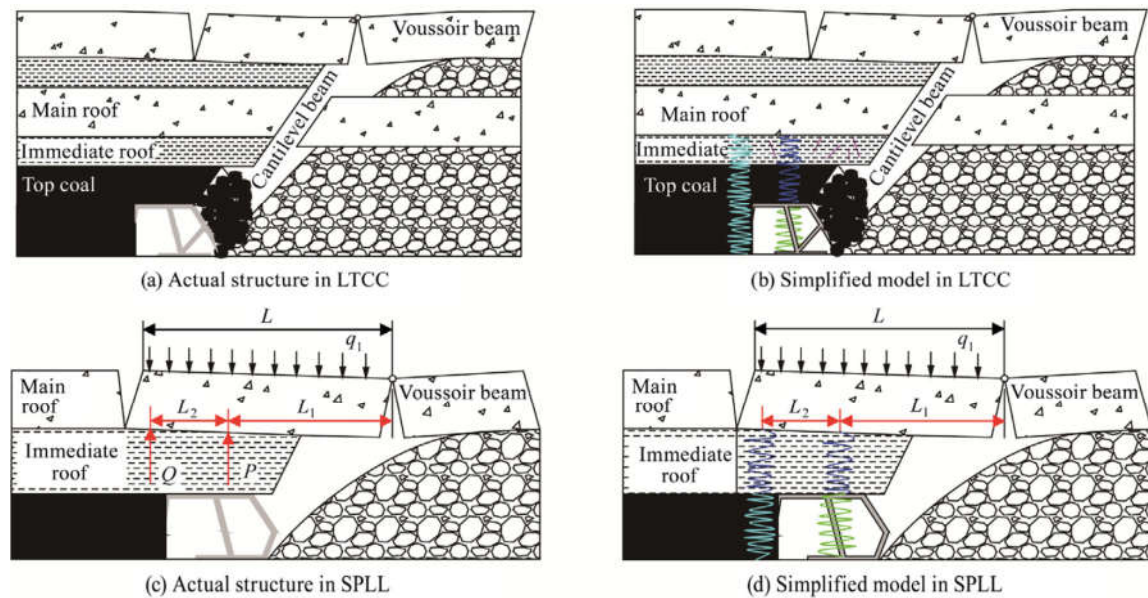


Fig. 4. System of face–support–roof in (a–b) LTCC and (c–d) SPLL faces [10]. L_1 and L_2 are distances from support to roof breaking point and coal wall; Q is coal wall force; P is shield force, and q_1 is the gravity of overburden.

Previous studies successfully developed several mechanical models of face stability from which key controlling parameters were identified; laws of parameters' impact on stability were analyzed; spall/fall extent was estimated, and criteria for assessing face stability were proposed. These analytical models were mainly based on the theory of force/moment balance (static solution) or energy conservation principle (dynamic solution). For LTCC face, the models were, however, complicated in use due to the complex calculation of kinetic/potential energy of ruptured/caved top coal and roof strata. Therefore, this paper aims at establishing a simple mechanical model for the fundamental understanding of face stability in the longwall top coal caving method. The paper's results provide mining engineers with a low-cost tool for quick evaluation of face instability risk in the preliminary stage of mine design.

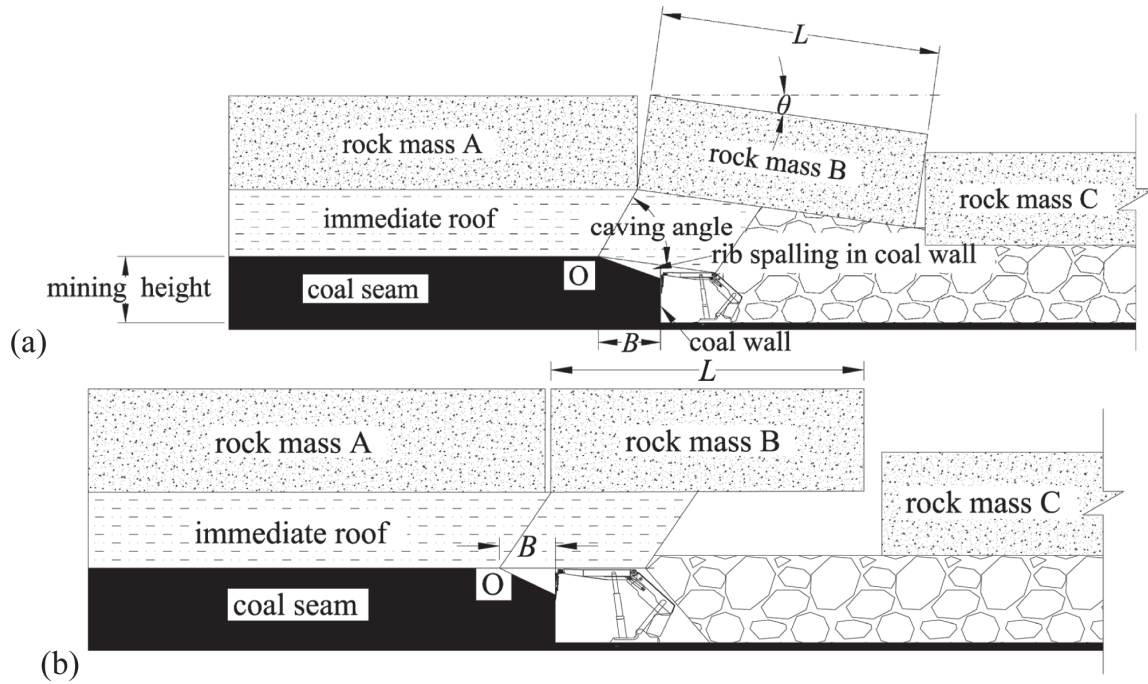
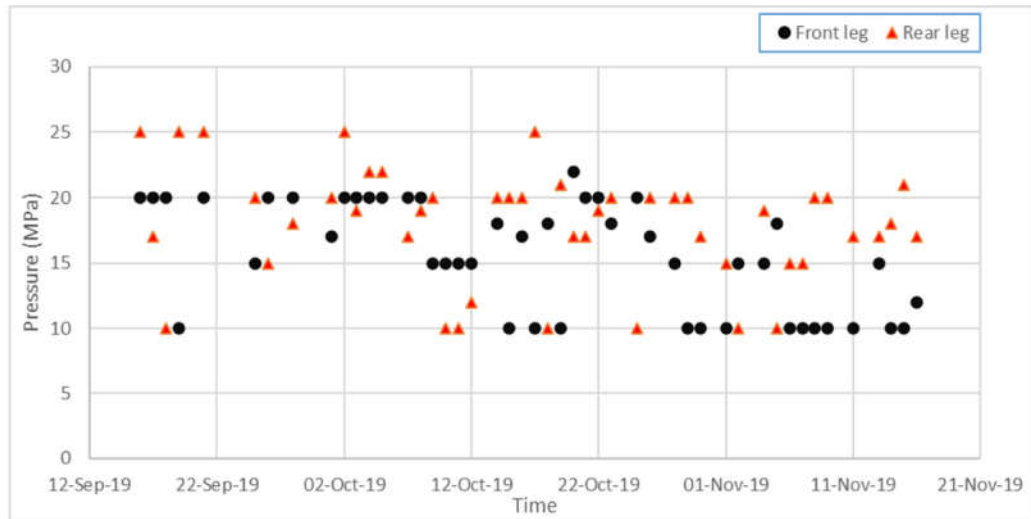


Fig. 5. System of face–support–roof in (a) voussoir beam-formed main roof and (b) cantilever beam-formed main roof [11]. B is the depth of rib spalling; L is breaking span of the main roof; O is origin point, and θ is the rotation angle of the main roof.

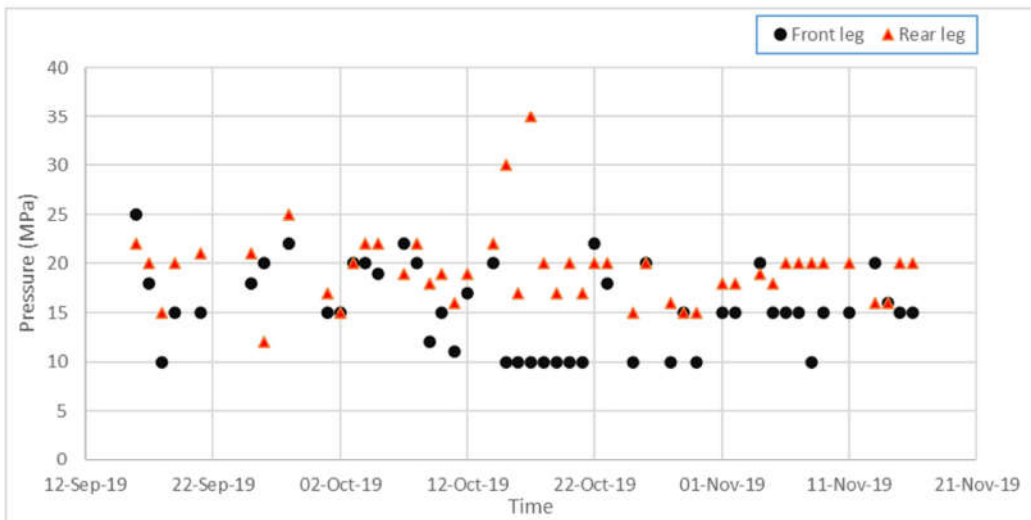
2 Field Observation at Quang Ninh Mechanised Faces

Two mechanized longwall top coal caving faces at Quang Ninh coalfield in Vietnam are taken as real databases for development and comparison of face stability mechanical model. They are Face 11-1.14 at Ha Lam coal mine and Face I-8-1 at Vang Danh coal mine. A field observation at Face I-8-1 was presented in Le and Dao [12] in which the periodic intervals of the immediate roof and main roof were reported at 10 and 90 m, respectively. According to the mining engineer at the site [13], minor face spall occurred more frequently in less than 0.5 m deep, while major spall was less frequent but more severe - the spall extended 1–2 m into coal face and 5–7 m above seam floor.

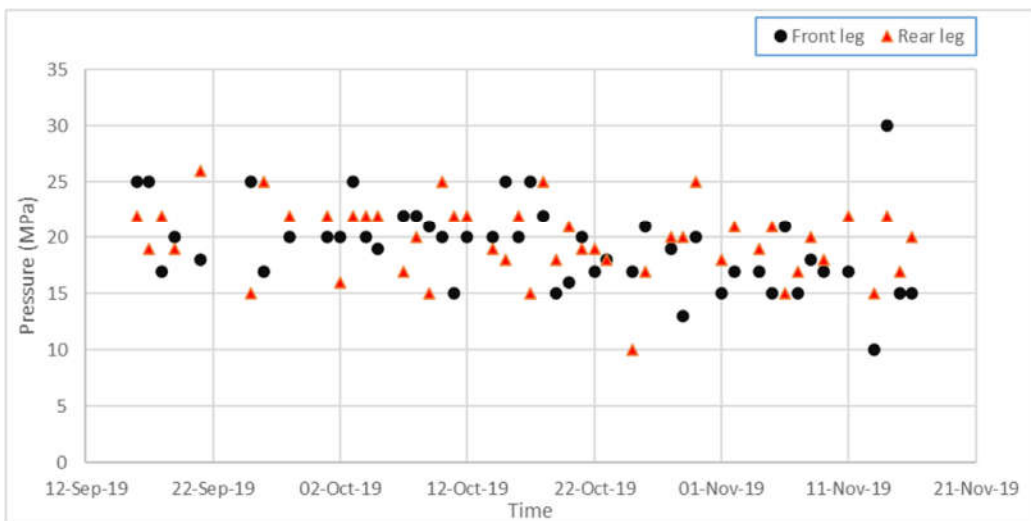
For Face 11-1.14 Ha Lam coal mine, general geotechnical conditions can be found in Le, Bui, Pham, Vu, and Dao [14]. It was reported by on-site engineers that the periodic caving interval of the immediate roof was 10 m, while no information on primary roof behavior was revealed. Face spall was observed up to 3.15 m deep into coal face and several meters into the top coal section. To better understand the face behavior at the site, field measurement of shield leg pressure was implemented for the current study. Front and rear legs of three shield support near tailgate (Shield #1), near the main gate (Shield #71), and at mid-panel width (Shield #35) were recorded and displayed in Fig. 6(a–c). The following observations were made from the figure as follows. Firstly, at the mid-panel width, the leg pressure mostly ranged from 15 to 25 MPa, while near two gate roads, the leg pressure mostly ranged from 10 to 20 MPa. The difference in the range was because near two gate roads, and the installed shields had the higher working capacity, while the area was additionally supported by supplemental hydraulic props. At the monitoring locations, the front leg pressure was from time to time less than the rear



(a)



(b)



(c)

Fig. 6. Pressure in front leg and rear leg of (a) Shield #1 near tailgate; (b) Shield #71 near maingate; and (c) Shield #35 at mid-panel width

leg pressure. This phenomenon, however, was not seen in Face I-8-1 [12] and other stable coal faces [15, 16]. The reason was mainly the face spall and roof fall ahead of shield support that ruins the tight contact between shield roof canopy and top coal section. The comparison confirms that the face instability at Ha Lam coal face was more significant compared to that at Vang Danh coal face.

3 Mechanical Model of Seam–Support–Roof Interaction

3.1 Mechanical Model

Excluding large geological structures which are beyond the scope of this study, face spall in Quang Ninh LTCC faces occurs typically in two typical conditions: (a) coal seam is weak/relatively weak, highly jointed and easy to cave (e.g., Ha Lam coal mine); and (b) coal seam is moderate strength and immediate and main roofs cave/rupture in larger intervals (e.g., Vang Danh coal mine). From these conditions, a model (system) representing the mechanical interaction between coal seam, shield support, and roof strata is established, as illustrated in Fig. 7. In this figure, top coal is the coal seam section above shield support and is allowed to cave; the immediate roof is the rock immediately above top coal and caves as top coal caves; and the main roof is the rock above the immediate roof, which ruptures but does not cave, and can still transmit horizontal force [17]. The system represents a static equilibrium immediately before the face spall. That is, both algebraic sum of all forces and algebraic sum of all turning/bending moments in the system must be equal to zero. It is assumed that the depth of face spall is D and associated origin point is O . The interaction system shows that the load supported by coal wall and shield support consists of weights of top coal W_{tc} , immediate roof W_{imr} and main roof W_{mr} . The top coal component L_{tc} covers the lengths of the coal wall, tip-to-face distance L_d , and roof canopy L_s . The immediate component is the cantilever beam, which caves at the same time or with a little delay after top coal caving. It is noted that top coal recovery leads to the greater mined-out height that consequently creates sufficient space for the immediate roof to collapse completely. The length of the immediate roof part L_{imr} is dependent on its structure as well as for overburden load. The main roof component is referred to as the periodic rupture interval L_{mr} resting on the immediate roof. The broken but un-caved main roofs can still transmit some horizontal forces, and their weight acts on lower strata and caved rock pile. Below the loading components and immediately before face spall, shield support increases to its maximum working capacity P_s while the coal wall reaches its maximum bearing capacity P_c . The shield applies a guard force P_g on the coal wall and, in turn, receives an opposite force P_g' from the wall. Note that the weight and force in the current model are corresponding to 1 m in the out-of-plane direction.

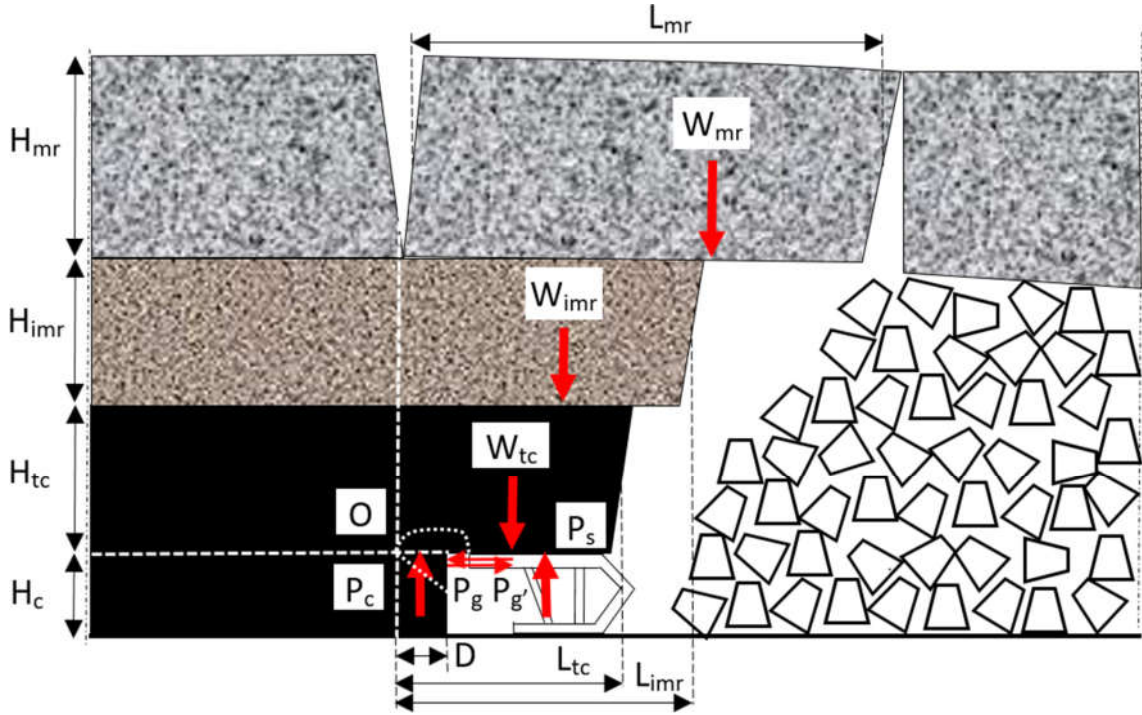


Fig. 7. Mechanical model of the seam–support–roof interaction for LTCC. H_{mr} , H_{imr} , H_{tc} , and H_c are heights of the main roof, immediate roof, top coal and cutting coal; W_{mr} , W_{imr} , and W_{tc} are weights of the main roof, immediate roof, and top coal; P_s , P_c , P_g and $P_{g'}$ are the maximum working capacity of shield support, maximum bearing capacity of coal wall, guard force of shield and opposite force of coal wall; L_{mr} , L_{imr} , and L_{tc} are rupture/caving lengths of the main roof, immediate roof, and top coal; O is origin point and D is the depth of face spall.

3.2 Extent of Face Spall

As mentioned earlier, at static equilibrium, the mechanical interaction system in Fig. 7 satisfies two conditions at the same time: the sum of all forces and the sum of all moments must be equal to zero. Hence:

$$W_{mr} + W_{imr} + W_{tc} = P_c + P_s \quad (1)$$

$$\frac{L_{mr}}{2} L_{mr} H_{mr} \gamma_{mr} + \frac{L_{imr}}{2} L_{imr} H_{imr} \gamma_{imr} + \frac{L_{tc}}{2} L_{tc} H_{tc} \gamma_c = \frac{D}{2} P_c + \left(\frac{L_s}{2} + L_d + D \right) P_s \quad (2)$$

Where γ_{mr} , γ_{imr} and γ_c are unit weights of primary roof rock, immediate roof rock, and coal, respectively; H_{mr} , H_{imr} , and H_c are heights of main roof strata, immediate roof strata, and top coal beams, respectively.

If the intervals of immediate roof caving and main roof rupture are known, the depth of face spall can be estimated from Eq. (2) as follows:

$$\frac{L_{mr}}{2} L_{mr} H_{mr} \gamma_{mr} + \frac{L_{imr}}{2} L_{imr} H_{imr} \gamma_{imr} + \frac{L_{tc}}{2} L_{tc} H_{tc} \gamma_c - \frac{L_s + 2L_d}{2} P_s = D \left(\frac{P_c}{2} + P_s \right) \quad (3)$$

$$D = \frac{L_{mr}^2 H_{mr} \gamma_{mr} + L_{imr}^2 H_{imr} \gamma_{imr} + L_{tc}^2 H_{tc} \gamma_c - (L_s + 2L_d)P_s}{P_c + 2P_s} \quad (4)$$

Substituting Eq. (1) into Eq. (4) gives:

$$D = \frac{L_{mr}^2 H_{mr} \gamma_{mr} + L_{imr}^2 H_{imr} \gamma_{imr} + L_{tc}^2 H_{tc} \gamma_c - (L_s + 2L_d)P_s}{L_{mr} H_{mr} \gamma_{mr} + L_{imr} H_{imr} \gamma_{imr} + L_{tc} H_{tc} \gamma_c + P_s} \quad (5)$$

If coal face spalls in conformity with Mohr-Coulomb failure criterion, the angle, and height of the spall can also be estimated. As depicted in Fig. 8, the angle of failure surface compared to vertical direction is α , height of spall is H , weight of spalling block is G , load acting on spalling block is W , internal friction angle of coal is φ , and cohesion strength of coal is c . Immediately before the spall, shear resistance force R is equal to shear force S , which means:

$$R = S \quad (6)$$

$$[(W + G)\sin\alpha + P_g \cos\alpha] \tan\varphi + c \frac{D}{\sin\alpha} = (W + G)\cos\alpha - P_g \sin\alpha \quad (7)$$

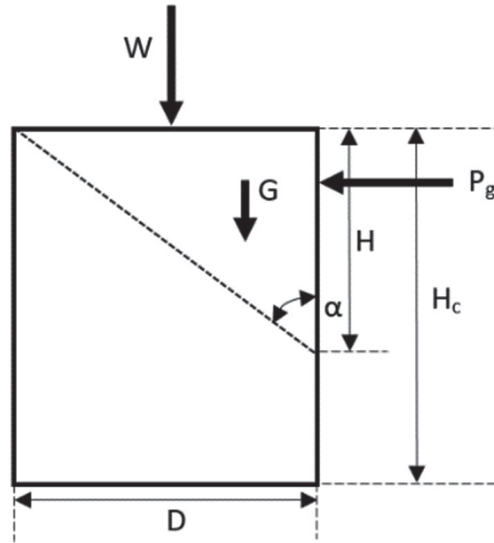


Fig. 8. Coalface spall in conformity with Mohr-Coulomb failure criterion. D is the depth of face spall; G is the weight of spalling block; H is the height of face spall; H_c is the height of the coal face; P_g is the guard force of shield; W is acting load; and α is the angle of spall

Since

$$W = L_{mr} H_{mr} \gamma_{mr} + L_{imr} H_{imr} \gamma_{imr} + L_{tc} H_{tc} \gamma_c - P_s \text{ and } G = \frac{1}{2} H D \gamma_c = \frac{D^2 \gamma_c}{2 \tan\alpha},$$

then

$$\left[\left(W + \frac{D^2 \gamma_c}{2 \tan\alpha} \right) \sin\alpha + P_g \cos\alpha \right] \tan\varphi + c \frac{D}{\sin\alpha} = \left(W + \frac{D^2 \gamma_c}{2 \tan\alpha} \right) \cos\alpha - P_g \sin\alpha \quad (8)$$

or

$$\left[\left(W + \frac{HD\gamma_c}{2} \right) \tan\varphi + P_g \right] \frac{D^2}{D^2 + H^2} + cD = \left(W + \frac{HD\gamma_c}{2} - P_g \tan\varphi \right) \frac{HD}{D^2 + H^2} \quad (9)$$

The angle of failure surface and height of the spall can be calculated from Eq. (8) or (9).

3.3 Calculation Result

Based on the field observations presented in the previous section, the depth of face spall at the two LTCC faces is calculated by using Eq. (5) for comparison purposes. It is noted that coal seam, roof strata, and shield characteristics are adopted from site and consultant reports [18, 19]. In the first round of calculation, practical main roof interval was assigned to the equation; however, the resultant depth was very unrealistic. This means that Eq. (5) is capable of estimating face spall depth when the spall is mainly caused by the ruptures of the immediate roof and top coal beams. When the main roof ruptures, it increases roof pressure rapidly that can break shield support and destroys the whole coal wall. Hence, Eq. (5) is rewritten, as shown in Eq. (10). The final calculation results are shown in Tables 1 and 2. It can be seen that the calculated depth at Face 11-1.14 falls within the range of the depth reported from the site. This estimated value is about 1.8 times less than the maximum depth recorded. In contrast, the calculated value at Face I-8-1 is 1.8 times greater than the maximum depth recorded in the field. The difference in results can be attributed mainly to the role of strata strength in the calculation. That is, although the developed solution cannot explicitly take into account coal/rock material strength nor small geological structures in strata (e.g., joints) that impact strata stability, it does consider an overall effect of strata strength through the rupture lengths and heights of the immediate roof and top coal beams. In practice, the rupture lengths of the immediate roof and top coal and the shield characteristics are the same for the two faces, as reported in Tables 1 and 2. However, the height of the immediate roof in Face 11-1.14 is 1.7 times less than that in Face I-8-1, while the height of top coal in the first face is 2.5 times greater than that in the second face. The difference here makes the estimated value in Ha Lam coal face less than that in Vang Danh coal face. Furthermore, as earlier stated in this paper, Ha Lam coal seams are weaker than Vang Danh coal seams. This explains why the calculation underestimates the spall depth at Ha Lam coal face while it overestimates the instability at Vang Danh coal face.

$$D = \frac{L_{imr}^2 H_{imr} \gamma_{imr} + L_{tc}^2 H_{tc} \gamma_c - (L_s + 2L_d) P_s}{L_{imr} H_{imr} \gamma_{imr} + L_{tc} H_{tc} \gamma_c + P_s}. \quad (10)$$

Table 1. Calculation of face spall depth at Face 11-1.14 Ha Lam coal mine

Parameter	Value	Parameter	Value	Estimated value	Field value
L_{mr}	0 (m)	L_d	0.63 (m)	$D = 1.72$ (m)	$D \leq 3.15$ (m)
H_{mr}	16.72 (m)	L_s	3.75 (m)		
γ_{mr}	26000 (N/m ³)	P_s	2.93E6 (N)		
L_{imr}	10 (m)	P_g	0.15E6 (N)		
H_{imr}	8.48 (m)				
γ_{imr}	26000 (N/m ³)				
L_{tc}	4.38 (m)				
H_{tc}	8.39 (m)				
γ_{tc}	15000 (N/m ³)				

Table 2. Calculation of face spall depth at Face I-8-1 Vang Danh coal mine

Parameter	Value	Parameter	Value	Estimated value	Field value
L_{mr}	0 (m)	L_d	0.63 (m)	$D = 3.55$ (m)	$D \leq 2.00$ (m)
H_{mr}	11.3 (m)	L_s	3.75 (m)		
γ_{mr}	26600 (N/m ³)	P_s	2.93E6 (N)		
L_{imr}	10 (m)	P_g	0.15E6 (N)		
H_{imr}	14.5 (m)				
γ_{imr}	26600 (N/m ³)				
L_{tc}	4.38 (m)				
H_{tc}	3.41 (m)				
γ_{tc}	16700 (N/m ³)				

4 Conclusions

This paper first presents a mechanical model of face spall in mechanized longwall top coal caving method in which the interaction between coal seam, shield support, and roof strata has been taken into consideration. An equation for estimation of face spall extent has been then developed from the model, using the field observations at Face 11-1.14 Ha Lam coal mine and Face I-8-1 Vang Danh coal mine. The estimation demonstrates that the equation applies to cases where the spall is mainly caused by the ruptures of the immediate roof and top coal beams. When the main roof ruptures, the roof pressure is rapidly increased and may subsequently cause shield damage and whole face collapse. Although the equation may either underestimate or overestimate the instability due to the lack of impact of strata strength, it provides mining engineers operating longwall top coal caving face with a low-cost tool for quick evaluation of face instability risk in the

preliminary stage of mine design. A more detailed investigation of the impact of strata strength on face stability is being implemented by the author using numerical modeling.

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