Research Article

A New Closed-Form Solution of the Side Abutment Pressure Distribution of Roadway

Liang Cheng ¹ and Yidong Zhang ²

¹School of Mines, Key Laboratory of Deep Coal Resource Mining, Ministry of Education of China, China University of Mining and Technology, Xuzhou 221116, China

²School of Mines, State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Xuzhou 221116, China

Correspondence should be addressed to Yidong Zhang; ydzhang@cumt.edu.cn

Received 10 May 2018; Accepted 3 July 2018; Published 1 August 2018

Academic Editor: Libo Yan

Copyright © 2018 Liang Cheng and Yidong Zhang. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Instability of coal wall is one of the hot-button and difficult issues in the study of coal mine ground control. The shallow side coal of roadway in the coal measures is usually weak and consequently easy to bring about failure. Hence, the side abutment pressure redistributes and dramatically influences the roadway stability. Since the previous closed-form solutions of the side abutment pressure do not take into account all the necessary parameters which include the properties of the coal and the interface between coal and roof/floor, the roadway height, and the support strength, a mechanical model is established based on the equilibrium of the plastic zone, and a new closed-form solution is derived in this paper. Moreover, a numerical investigation is conducted to validate the accuracy of the closed-form solution. The numerical results of the side abutment pressure distribution are in good agreement with the closed-form solution. Afterwards, a parametric analysis of the width of the plastic zone is carried out, and the results show that the width of the plastic zone is nearly negatively linearly correlated with the friction angle and the cohesion of the coal, the interfacial cohesion, and the support strength. By contrast, it is positively linearly correlated with the roadway height and negatively exponentially correlated with the interfacial friction angle. The results obtained in the present study could be useful for the evaluation process of roadway stability.

1. Introduction

Underground coal is an integral part of the primary energy sources and is used for a wide range of applications. Physical extraction of coal is still an important method in the mining industry. Before the physical extraction, a group of roadways needs to be constructed for the transportation of the workers, equipment, tools, and raw coal. Along with the mining production, the excavation of roadway is continuing. Therefore, to some extent, the stability of roadway has a large effect on the efficiency of underground coal mining.

The roadway stability is dramatically influenced by the abutment pressure distribution [1–3]. The stress distribution of surrounding rock of roadway could be calculated by using elasticity when it is assumed that the surrounding rock follows the assumptions of elasticity [4]. However, roadway is excavated in a coal seam, and the shallow coal is usually

weak and consequently easy to bring about failure [5, 6]. Neither the laws of soil mechanics nor the theories of elasticity explain completely the behavior of the relatively soft coal [7]. In this condition, the side abutment pressure distribution can be obtained roughly based on the closed-form solutions of (1)–(4) and (7) in Table 1 [8–10]. The above closed-form solutions neglect the interface between coal and roof/floor. Actually the interface between coal and roof/floor is usually weak and has a large effect on the side abutment pressure distribution, which usually degrades roadway stability. Shou demonstrated that the lesser angle between the axial direction of the entry and the dip direction of the weak plane contributed larger deformation for the roof [11]. Jeon et al. found that the shear deformation at the weak plane leads to a large displacement of the rock around the entry [12]. Zhao et al. revealed that the shear slipping mainly occurred along the weak plane due to the failure of

TABLE 1: A summary of research status of the side abutment pressure distribution.

Number	Name	Mechanical model	Equations	Symbols
1	Chen and Liu [8]		$\sigma_y = C \exp(fx/h_1 \zeta)$ $\sigma_x = C \zeta [\exp(fx/h_1 \zeta) - 1]$ $\sigma_{ye} = \gamma H [1 + (k_0 - 1) \exp(-2x/b)]$ $h_1 = m(E_y/E_k)^{(1/2-3)/2}$ $L = (k_1 \zeta / f) \ln(k_0 \gamma H / C)$ $f = \tan \varphi$ $\zeta = d\sigma_x / d\sigma_y$	σ_y and σ_{xe} , stresses in the elastic zone; σ_{ye} , vertical stress in the plastic zone; x_s , width of the plastic zone; L , influence distance of the side abutment pressure; m , roadway height; b , roadway width; C , coal cohesion; φ , coal friction angle; E_y , elastic modulus of coal; E_k , elastic modulus of immediate roof; k_0 , side abutment pressure concentration factor; γ , average density of overlying strata; H , height of overlying strata
2	Hou and Ma [9]		$Q = S_2 + S_3 - S_1$ $Q = \gamma H (2l_1 + H \tan \alpha) / 2$ $S_1 = \gamma H - (mc/2f) [\exp(2fa/mc) - 1]$ $S_2 = Cmc/2f [\exp(2fx_s/mc) - \exp(2fa/mc)] - \sigma_0 (x_s - a)$ $S_3 = \begin{cases} (2l_1 + H \tan \varphi) / 2 [C \exp(2fx_s/mc) - \gamma H] \\ 1.57 \sqrt{0.7H} [C \exp(2fx_s/mc) - \gamma H] \end{cases}$	Q , overburden weight over gob transferred to the coal seam; S_1 , S_2 , and S_3 , counterforce of the coal seam; l_1 , length of cantilever roof; α , failure angle of roof; β , dip angle of the coal seam; $a = (mc/2f) \ln(\sigma_0/C)$; $\sigma_0 = (\cos^2 \beta + \eta \sin^2 \beta) \gamma H$
3	Hou and Ma [9]		$p(x) = \gamma H + \eta \cdot \eta(H) ((\gamma H)^2 / 2 \tan \alpha)$	η , lateral earth pressure factor; $\eta(H)$, depth factor
4	Chen and Liu [8]		$z = 0.1L/1.33k_f$ $l_0 = (L/2 \sqrt{k_f}) [(3 - L \cos \alpha (\tan \alpha + \tan \beta)/H)]^{1/2}$ $k_f = f_n / f_c$	f_n , strength factor of coal; f_c , strength factor of overburden strata

Solving (8) gives

$$\begin{aligned} f(x) &= W_3 \exp\left(\frac{W_2}{\tan \varphi_0} x\right), \\ g(y) &= W_4 \exp(W_2 y). \end{aligned} \quad (9)$$

Substituting (9) into (6) yields

$$\sigma_y = W_5 \exp\left(\frac{W_2}{\tan \varphi_0} x\right) + W_1, \quad (10)$$

where $y = m/2$; $W_5 = W_3 W_4 \exp((W_2 m)/2)$; and m is the roadway height.

Substituting (10) into (1) yields

$$\tau_{xy} = -\left\{ \left[W_5 \exp\left(\frac{W_2}{\tan \varphi_0} x\right) + W_1 \right] \tan \varphi_0 + C_0 \right\}. \quad (11)$$

2.3.2. The Equation of Limit Equilibrium Zone. Based on the mechanical model in Figure 1, the resultant force in the limit equilibrium zone ABCD is zero.

$$\frac{m}{2} \sigma_x + \int_0^x \tau_{xy} dx - \frac{m}{2} P_x = 0, \quad (12)$$

where P_x is the support strength.

The interfacial friction angle and cohesion are much lower than that of coal. Therefore, the vertical and horizontal stress in the plastic zone are assumed as the principle stresses, and the relationship is shown as follows based on Mohr–Coulomb failure criterion:

$$\sigma_x = \sigma_y \frac{1 - \sin \varphi}{1 + \sin \varphi} - \frac{2C \cos \varphi}{1 + \sin \varphi}. \quad (13)$$

The derivation of each side of (12) is as follows:

$$\frac{m}{2} \left(\frac{1 - \sin \varphi}{1 + \sin \varphi} \right) \frac{d\sigma_y}{dx} + \tau_{xy} = 0. \quad (14)$$

Substituting (1) into (14) yields

$$\frac{m}{2} \left(\frac{1 - \sin \varphi}{1 + \sin \varphi} \right) \frac{d\sigma_y}{dx} - \tan \varphi_0 \sigma_y - C_0 = 0. \quad (15)$$

Solving (15) yields

$$\sigma_y = W_6 \exp\left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m(1 - \sin \varphi)} x\right] - \frac{C_0}{\tan \varphi_0}. \quad (16)$$

2.3.3. The Side Abutment Pressure Distribution in Plastic Zone. Comparing (10) and (16) gives

$$\begin{aligned} W_5 &= W_6, \\ W_2 &= \frac{2 \tan^2 \varphi_0}{m} \left(\frac{1 + \sin \varphi}{1 - \sin \varphi} \right), \\ W_1 &= -\frac{C_0}{\tan \varphi_0}. \end{aligned} \quad (17)$$

Submitting (16) and (17) into (2) and (17), respectively, yields

$$W_6 \exp\left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m(1 - \sin \varphi)} x\right] - \frac{C_0}{\tan \varphi_0} = k_0 \gamma H,$$

$$\frac{m}{2} \left(\sigma_y \frac{1 - \sin \varphi}{1 + \sin \varphi} - \frac{2C \cos \varphi}{1 + \sin \varphi} \right) + \int_0^x \tau_{xy} dx - \frac{m}{2} P_x = 0. \quad (18)$$

Integrating x in (11) yields

$$\int_0^x \tau_{xy} dx = \frac{W_6 m (1 - \sin \varphi)}{2(1 + \sin \varphi)} \left\{ 1 - \exp\left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m(1 - \sin \varphi)} x\right] \right\}. \quad (19)$$

Equation (18) can be rewritten as follows:

$$W_6 \exp\left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m(1 - \sin \varphi)} x\right] - \frac{C_0}{\tan \varphi_0} = k_0 \gamma H,$$

$$k_0 \gamma H \frac{1 - \sin \varphi}{1 + \sin \varphi} - \frac{2C \cos \varphi}{1 + \sin \varphi} + \frac{W_6 (1 - \sin \varphi)}{1 + \sin \varphi}$$

$$\cdot \left\{ 1 - \exp\left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m(1 - \sin \varphi)} x\right] \right\} - P_x = 0. \quad (20)$$

Solving (20) yields

$$W_6 = \frac{C_0}{\tan \varphi_0} + \left(\frac{1 + \sin \varphi}{1 - \sin \varphi} \right) P_x + \frac{2C \cos \varphi}{1 - \sin \varphi}. \quad (21)$$

Substituting separately (17) and (20) into (10) and (11) yields

$$\sigma_y = \left[\frac{C_0}{\tan \varphi_0} + \left(\frac{1 + \sin \varphi}{1 - \sin \varphi} \right) P_x + \frac{2C \cos \varphi}{1 - \sin \varphi} \right]$$

$$\cdot \exp\left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m(1 - \sin \varphi)} x\right] - \frac{C_0}{\tan \varphi_0},$$

$$\tau_{xy} = \left[C_0 + \left(\frac{1 + \sin \varphi}{1 - \sin \varphi} \right) P_x \tan \varphi_0 + \frac{2C \cos \varphi \tan \varphi_0}{1 - \sin \varphi} \right]$$

$$\cdot \exp\left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m(1 - \sin \varphi)} x\right] - \frac{C_0}{\tan \varphi_0}. \quad (22)$$

The width of the plastic zone is given by

$$\begin{aligned} x_s &= \frac{m}{2 \tan \varphi_0} \left(\frac{1 - \sin \varphi}{1 + \sin \varphi} \right) \\ &\cdot \ln \left[\frac{k_0 \gamma H + (C_0 / \tan \varphi_0)}{(C_0 / \tan \varphi_0) + ((1 + \sin \varphi) / (1 - \sin \varphi)) P_x + ((2C \cos \varphi) / (1 - \sin \varphi))} \right], \end{aligned} \quad (23)$$

where x_s is the width of the plastic zone.

2.3.4. The Side Abutment Pressure Distribution in Elastic Zone. The side abutment pressure distribution in the elastic zone follows the negative exponent distribution [8].

$$\sigma_{ye} = \chi \exp(-\alpha_0 x) + \gamma H (x \geq x_s), \quad (24)$$

where σ_{ye} is the side abutment pressure in the elastic zone; χ is the factor to describe the peak side abutment pressure; and α_0 is the factor to describe the change of the side abutment pressure.

To assure the stress continuum, substituting $x = x_s$ and $f(x) = k_0 \gamma H$ into (24) yields

$$\chi = \frac{(k_0 - 1)\gamma H}{\exp(-\alpha_0 x_s)}. \quad (25)$$

The side abutment pressure in the elastic zone is shown as

$$\sigma_{ye} = (k_0 - 1)\gamma H \exp[-\alpha_0 (x - x_s)] + \gamma H (x \geq x_s). \quad (26)$$

2.3.5. Solving α_0 . The vertical counterforce at the interface should be equal to the weight of the overlying strata.

$$\gamma HL = \int_0^{x_s} \sigma_y dx + \int_{x_s}^{L-(b/2)} \sigma_{ye} dx. \quad (27)$$

Submitting (2) and (26) into (27) yields

$$\begin{aligned} & \frac{(k_0 - 1)\gamma H}{\alpha_0} \left\{ 1 - \exp \left[\alpha \left(x_s - L + \frac{b}{2} \right) \right] \right\} - \frac{C_0 x_s}{\tan \varphi_0} - \gamma H \left(x_s + \frac{b}{2} \right) \\ &= -\frac{m}{2} \left[\frac{C_0 (1 - \sin \varphi)}{\tan^2 \varphi_0 (1 + \sin \varphi)} + \frac{P_x}{\tan \varphi_0} \right. \\ & \quad \left. + \frac{2C \cos \varphi}{\tan \varphi_0 (1 + \sin \varphi)} \right] \left\{ \exp \left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m (1 - \sin \varphi)} x_s \right] - 1 \right\}. \end{aligned} \quad (28)$$

Substituting (28) into (27) yields

$$\alpha_0 = \frac{(k_0 - 1)\gamma H}{\left(\frac{C_0 x_s}{\tan \varphi_0} + \gamma H \left(x_s + \frac{b}{2} \right) - \frac{m}{2} \left[\frac{C_0 (1 - \sin \varphi)}{\tan^2 \varphi_0 (1 + \sin \varphi)} + \frac{P_x}{\tan \varphi_0} + \frac{2C \cos \varphi}{\tan \varphi_0 (1 + \sin \varphi)} \right] \left\{ \exp \left[\frac{2 \tan \varphi_0 (1 + \sin \varphi)}{m (1 - \sin \varphi)} x_s \right] - 1 \right\} \right)}. \quad (29)$$

3. Numerical Validation

Figure 2 shows the 2D numerical model used in the present study, using the finite difference program FLAC 3D. It is assumed that the behavior of the roof and floor is linear-elastic, and the coal follows Mohr–Coulomb failure criterion. Embedded interfaces are attached to the zone faces along the coal and the roof/floor. The interface stiffness (normal stiffness k_n and tangential stiffness k_s) is estimated using a rule-of-thumb in which k_n and k_s are set to 10 times the equivalent stiffness of the stiffest neighboring zone [16], and the constitutive model is perfectly elastic-plastic and follows Mohr–Coulomb failure criterion.

The numerical model is 100 m wide in the x -direction and 50 m high in the z -direction and consists of approximately 50000 zones. The width and height of roadway are 4.8 m and 4 m, respectively. The bottom and sides of the model are fixed in displacement and the top is applied with a load of 10 MPa.

FIGURE 2: Numerical model.

TABLE 2: Properties of the surrounding rock and the interface.

Properties of the surrounding rock	Unit	Value
Roof/floor density	kg/m ³	2500
Coal density	kg/m ³	1300
Roof/floor modulus	GPa	10
Coal modulus	GPa	4
Roof/floor Poisson ratio		0.2
Coal Poisson ratio		0.3
Coal cohesion	MPa	1
Coal friction angle	°	25
Coal tension	MPa	0.5
Properties of the interface		
Normal stiffness	GPa	673
Shear stiffness	GPa	673
Cohesion	MPa	0.1
Friction angle	°	10
Tension	MPa	0

An anisotropic stress field has been assigned in the model with a lateral earth pressure factor of 1. The parameters of the surrounding rock and the interface are from a case found in a coal mine in China as shown in Table 2.

The numerical results of the roadway stability are compared with the above closed-form solution, which is shown in Figure 3. Note that k_0 in the closed-form solution is obtained from the modelling. The following can be seen from Figure 3:

- (1) The side abutment pressure can be divided into two areas: plastic zone and elastic zone. In the plastic zone, the side abutment pressure increases from the support strength at the wall surface to the peak pressure at the boundary of the plastic zone and elastic zone. In the elastic zone, the side abutment pressure decreases to the in situ stress gradually.
- (2) The width of the plastic zone decreases and the width of the elastic zone increases with the increase of the

(a)

(b)

(c)

(d)

FIGURE 3: Continued.

FIGURE 3: The side abutment pressure distribution. (a) The interfacial friction angle. (b) The interfacial cohesion. (c) The friction angle of the coal. (d) The cohesion of the coal. (e) The roadway height. (f) The support strength.

FIGURE 4: Continued.

FIGURE 4: Parametric analysis of the width of plastic zone. (a) The interfacial friction angle. (b) The interfacial cohesion. (c) The coal friction angle. (d) The coal cohesion. (e) The roadway height. (f) The support strength.

properties of the coal and the interface, the support strength, and the decrease of the roadway height.

- (3) From the comparison between the side abutment pressure of the closed-form solution and FLAC 3D, the numerical results of the side abutment pressure are generally in good agreement with the one obtained using the closed-form solution when changing the properties of the coal and the interface, the roadway height, and the support strength. However, the error between the side abutment pressure of the closed-form solution and FLAC 3D is relatively large when the interfacial cohesion and friction angle are large.

4. Parametric Analysis of the Width of Plastic Zone

Based on (23), the influence of the properties of the side coal and the interface, the roadway height and the support strength on the width of the plastic zone is conducted as shown in Figure 4. The initial parameters are the same of Table 2, and the side abutment pressure concentration factor is set as 1.6.

It can be seen from Figure 4 that the width of the plastic zone is nearly negatively linearly correlated with the friction angle from 20° to 35° and cohesion from 0.5 MPa to 2.5 MPa of the coal and the interfacial cohesion from 0.02 MPa to 1 MPa and the support strength from 0 MPa to 1 MPa. By contrast, it is positively linearly correlated with the roadway height from 2 m to 4 m and negatively exponentially correlated with the interfacial friction angle from 10° to 30° . In roadway support, the support strength is usually less than 0.2 MPa, and therefore the support strength has little effect on the width of the plastic zone especially in roadway with hard coals.

5. Summary and Conclusions

The side abutment pressure distribution is fundamental to evaluate the roadway stability. The side abutment pressure

can be divided into two areas: plastic zone and elastic zone. The side abutment pressure increases in the plastic zone and decreases in the elastic zone. The width of the plastic zone decreases and the width of the elastic zone increases with the increase of the properties of the coal and the interface, the support strength, and the decrease of the roadway height. This paper derived a new closed-form solution which takes into consideration the properties of the side coal and the interface, the roadway height, and the support strength. Moreover, a numerical investigation was conducted to validate the accuracy of the closed-form solution. The numerical results of the side abutment pressure are generally in good agreement with the one obtained using the closed-form solution when changing the properties of the coal and the interface, the roadway height, and the support strength. However, the error between the side abutment pressure of the closed-form solution and FLAC 3D is relatively large when the interfacial cohesion and friction angle are large. The results also show that the effect of the properties of the coal and the interface, the roadway height, and the support strength on the width of the plastic zone in detail when the shallow side coal is subject to plastic state. The results obtained in the present study could be useful for the evaluation process of roadway stability.

Abbreviations

σ_y :	Vertical stress in the plastic zone
σ_x :	Horizontal stress in the plastic zone
σ_{ye} :	Vertical stress in the elastic zone
x_s :	Width of the plastic zone
L :	Influence distance of the side abutment pressure
m :	Roadway height
b :	Roadway width
C :	Coal cohesion
φ :	Coal friction angle
C_0 :	Interfacial cohesion
φ_0 :	Interfacial friction angle
E_y :	Elastic modulus of coal

E_k :	Elastic modulus of immediate roof
k_0 :	Side abutment pressure concentration factor
γ :	Average density of overlying strata
H :	Height of overlying strata
Q :	Overburden weight over gob transferred to the coal seam
S_1, S_2, S_3 :	Counterforce of the coal seam
l_1 :	Length of cantilever roof
α :	Failure angle of roof
β :	Dip angle of coal seam
η :	Lateral earth pressure factor
$\eta(H)$:	Depth factor
f_n :	Strength factor of coal
f_c :	Strength factor of overburden strata
σ_c :	Uniaxial compressive strength of coal
P_x :	Support strength
ϕ :	Roof rotation angle
γ_0 :	Roof-floor convergence at the surface of wall rib
K_s :	Shear stiffness between coal and rock
τ_{xy} :	Shear stress
α_0 :	Factor to describe the change of the side abutment pressure
χ :	Factor to describe the peak side abutment pressure.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

This study is supported by “The Fundamental Research Funds for the Central Universities” (Grant no. 2017BSCXB49).

References

- [1] Q. Yao, X. Li, B. Sun et al., “Numerical investigation of the effects of coal seam dip angle on coal wall stability,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 100, pp. 298–309, 2017.
- [2] W. L. Shen, J. B. Bai, X. Y. Wang et al., “Response and control technology for entry loaded by mining abutment stress of a thick hard roof,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 90, pp. 26–34, 2016.
- [3] H. Kang, J. Li, J. Yang, and F. Gao, “Investigation on the influence of abutment pressure on the stability of rock bolt reinforced roof strata through physical and numerical modeling,” *Rock Mechanics and Rock Engineering*, vol. 50, no. 2, pp. 387–401, 2017.
- [4] Z. Xu, *Elasticity*, Higher Education Press, Beijing, China, 4th edition, 2006, in Chinese.
- [5] S. Yan, J. Bai, X. Wang, and L. Huo, “An innovative approach for gateroad layout in highly gassy longwall top coal caving,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 59, pp. 33–41, 2013.
- [6] A. Suchowska, J. Carter, and R. Merifield, “Vertical stress changes in multi-seam mining under supercritical longwall panels,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 61, pp. 306–320, 2013.
- [7] A. H. Wilson, “The stability of underground workings in the soft rocks of the coal measures,” *International Journal of Mining Engineering*, vol. 1, no. 2, pp. 91–187, 1983.
- [8] H. Chen and T. Liu, “Parametric study of the abutment stress of workface,” *Journal of Xi'an University of Science and Technology*, vol. 1, pp. 106–125, 1985, in Chinese.
- [9] C. Hou and N. Ma, *Theory and Application of Mining Roadways*, China Coal Industry Publishing House, Beijing, China, 1st edition, 1994, in Chinese.
- [10] Y. Yu, X. Hong, and F. Chen, “Study on load transmission mechanism and limit equilibrium zone of coal-wall in extraction opening,” *Journal of China Coal Society*, vol. 37, pp. 1630–1636, 2012, in Chinese.
- [11] K. A. Shou, “A three-dimensional hybrid boundary element method for non-linear analysis of a weak plane near an underground excavation,” *Tunnelling and Underground Space Technology*, vol. 15, no. 2, pp. 215–226, 2000.
- [12] S. Jeon, J. Kim, Y. Seo et al., “Effect of a fault and weak plane on the stability of a tunnel in rock—a scaled model test and numerical analysis,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 41, pp. 658–663, 2004.
- [13] H. Zhao, M. FengShan, D. Ding et al., “Structural weakness planes effect of roadway surrounding rocks deformation and failure affected by underground mining,” *Journal of Geological Hazards and Environment Preservation*, vol. 20, no. 2, pp. 51–56, 2009.
- [14] Z. Zhao, W. Wang, L. Wang et al., “Compression-shear strength criterion of coal-rock combination model considering interface effect,” *Tunnelling and Underground Space Technology*, vol. 47, pp. 193–199, 2015.
- [15] W. Shen, J. Bai, and W. Li, “Prediction of relative displacement for entry roof with weak plane under the effect of mining abutment stress,” *Tunnelling and Underground Space Technology*, vol. 71, pp. 309–317, 2018.
- [16] Itasca Consulting Group, *FLAC Fast Lagrangian Analysis of Continua*, Version 4.0, Itasca Consulting Group, Minneapolis, MN, USA, 2009.