Research Article

Prediction Model of Failure Zone in Roadway Sidewall considering the Lithologic Effect of Rock Formation

Zenghui Zhao ^{1,2}, Qing Ma,^{1,2} Shaojie Chen ^{1,2}, He Ma,^{1,2} and Xiaojie Gao^{1,2}

¹State Key Laboratory of Mining Disaster Prevention and Control Co-Founded by Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology, Qingdao 266590, China

²College of Mining and Safety Engineering, Shandong University of Science and Technology, Qingdao 266590, China

Correspondence should be addressed to Zenghui Zhao; tgzyzzh@163.com

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Coal seam damage area and its stress distribution law in roadway with medium thickness or extrathick coal seam are important issues for understanding the instability mechanism of roadway surrounding rock in weakly cemented soft rock strata in western China. Firstly, a variable parameter microelement analysis model is established based on the assumption of a plane stress integrating with the coal seam-rock's interface and the rock formation on both sides; moreover, a formula is established by the strain compatibility relationship to express the state of stress in rock bodies on both sides of the interface. Then, a method for calculating the stress limit equilibrium zone width of the coal side and regional stress distribution is presented, which considers the coupling effect of the coal side-rock formation and is based on the loose medium limit equilibrium theory. Finally, the validity of the model is verified through a comparison with previous research and by being applied to an engineering example. The results show the following: (1) the interface adhesion effect results in an abrupt change of the stress state of both the rock formation and coal seam and is related to their deformation parameters; i.e., there is a coupling effect; (2) the limit equilibrium zone width is not only related to the buried depth of the roadway, excavated coal seam thickness, coal seam strength parameters, stress concentration factor, lateral pressure coefficient, and supporting strength of the side of the roadway, but it also has an effect on the aforementioned coupling effect; (3) due to the roof-coal seam-floor comprehensive structural effect, the model presented in this paper is applicable to both the coal seam failure and the failure along the coal seam-rock's interface.

1. Introduction

The weakly cemented soft rocks, e.g., Cretaceous and Jurassic mudstone, argillaceous siltstone, sandstone, and silt, are widely distributed in Xinjiang, Gansu, Ningxia, western Inner Mongolia, and other areas in western China. The unique physical and mechanical properties of weakly cemented soft rocks are formed in western China due to its special geographical and climate conditions, sedimentary process, and geological conditions, and the rocks are characterized by a low strength, poor cementation, possible weathering, possible argillization and disintegration when encountering water, unstable mechanical properties, and large areas of disturbance, and quick deformation in the surrounding rock after the coal seam has been excavated, resulting in frequent engineering accidents or disasters, such as a large caving in

the roof and high walls, and serious floor heave, all of which can cause considerable economic losses and threats to the security of energy engineering construction in western China [1–4].

Due to the extreme instability of the weakly cemented rock in western China, the roadways are always excavated in the coal seam, forming a full coal roadway structure, with the characteristics of failure in the surrounding rock different from those in the roof's rock-coal seam-floor rock. Thus, determining the stress distribution of the roadway surrounding the rock and range of the limit equilibrium zone is an important issue for resolving the roadway's instability and selecting suitable support measures [5, 6]. The stability of the roadway's side and the coal pillars that support the roadway has been analyzed using different methods for many years. The failure behaviors of the rock surrounding the

roadway, the failure area of the surrounding rock, and the distribution of the stress and offset were analyzed using several rock models, i.e., an ideal elastoplastic model [7, 8], elasticity-brittleness model [9, 10], and strain softening model [11–14], with the results of this analysis providing theoretical guidance for the examination of the soft rock roadway's stability and choice of supporting method. In early research on coal pillars, an empirical formula for calculating the coal pillar was presented based on a statistical analysis of field tests of unstable and stable coal pillars [15–17], and this formula has been applied as a global, classical theory for many years. In terms of a theoretical study, the stability of the coal pillar was analyzed using the limit equilibrium method. Firstly, the whole coal pillar's nonelastic area was treated as a plane in the limit equilibrium state; secondly, it was treated with a fragmentation limit equilibrium in the nonelastic region; and, thirdly, the fragmentation limit equilibrium was treated by considering the plastic softening properties of the coal body [18]. Wang et al. established the formula for calculating the coal seam's failure zone in a non-fully mined and nonworked area with Newtonian mechanics and found that the limit equilibrium zone in the trapezoid coal pillar is half as wide as that in the conventional rectangle coal pillar [19]. Yuan and Chen analyzed the mechanical behavior of the plastic zone and failure zone in the mining roadway using an elastoplastic softening model, which was based on the characteristics of the rock body strain's softening and deformation [20]. Zheng and Yang calculated the coal side's failure zone width by simplifying the distribution of the coal side's stress curve [21]. Yu et al. established the theoretical formula of the coal side's horizontal offset and analyzed the main influencing factors, taking into account the coal body's deformation and relative offset of the roof and floor; their formula was based on the hyperbolic function mechanical model of the load transmission in the coal side under support pressure [22]. By considering the coal pillar as the semi-infinite elastic foundation beam in the soft floor, Yu et al. established the formula for the coal pillar's limit equilibrium zone using the Winkler elastic foundation beam theory and found that the coal pillar's failure width is related to the floor's elastic behavior [23]. In addition, the stress and offset distribution in the working section has been analyzed [24, 25]. Jaiswal and Shrivastva presented a method for analyzing the strain softening behavior of the coal body using a practical engineering numerical model [6]. Wattimena et al. analyzed the probability of failure in a specifically shaped coal pillar using a logistic regression [26].

The aforementioned research shows that the stability of roadway rocks or the roadway-supporting coal pillar is related to the buried depth of the roadway, rock formation width, physical properties of the roadway's side, supporting strength, and overlying rock gravity; moreover, the theoretical formula is significant when estimating the failure width of the roadway's side or a coal pillar and guides the design of the roadway's support. However, the bearing structure in the mine is a complex structure of roof, coal seam, and floor, and any mine disaster caused by their interaction is dependent on the integral mechanical behavior of the roof-coal body-floor complex [27]. The deficiency of the above

methods lies in the fact that they do not consider the roof-coal body-floor as an integral bearing structure and do not integrate the roof lithology into the analysis of the side rock's failure. For that reason, in this paper we analyze the coupling effect of the soft rock-coal's seam and establish a novel formula for calculating the limit equilibrium zone width and regional stress distribution using the loose medium equilibrium theory. The results obtained in this paper are compared with those in previous research and applied to engineering examples.

2. Coupling Effect of the Weakly Cemented Soft Rock-Coal Composite Body

2.1. Microelement Model. According to geological exploration data [28], the roof and floor of coal seams in the mining area in western China are dominated by weakly cemented rocks, such as carbon mudstone, fine sandstone, mudstone, and silty mudstone. A typical geological occurrence of the interbedding of the weakly cemented soft rock-coal's seam is shown in Figure 1. The extreme instability of the excavated rock formation has a significant influence on a mine's safety; thus the roadway is always excavated in a coal seam, forming a full coal roadway.

In this paper, the thickness of the coal's seam-rock interface is neglected. In order to analyze the influence of the soft rock-coal seam's interfacial effect on the stress state of the soft rock and coal seam, a variable parameter microbody integrating the soft rock-coal's body around the interface is cut which is marked as A or B in Figure 1, with the stress state shown in Figure 2.

2.2. Regional Stress along the Coal Seam-Soft Rock's Interface.

Here, it is assumed that there is no frictional sliding on the interface between the coal seam and rock body. As the deformation of the coal seam and rock is limited by the interface constraint, the induced stress occurs near the interface between the coal seam and rock body, resulting in a variation of the coal seam and rock body's stress state near the interface. The elasticity modulus of the soft rock formation and coal seam is defined as E_r and E_m , and Poisson's ratio is defined as ν_r and ν_m , respectively. Due to the difference of the elastic constant, a different deformation occurs in the coal seam and rock under the same stress. Binding the coal seam and rock as an integral factor for creating an identical deformation inevitably results in the induced stress on the interface, and a constraint effect is generated. Namely, the stress discontinuity and offset continuity occur on both sides of the interface.

In order to analyze the induced stress, the stress state in the microbody in Figure 2 is divided into normal stress and shear stress using the superposition principle, as shown in Figure 3.

Assume $E_r > E_m$ and $\nu_r < \nu_m$, and define $\alpha = E_r > E_m$ and $\beta = \nu_r/\nu_m$. The compressive pressure is positive and the shear stress is not induced by the normal stress. Thus, the normal stress is the sum of the original normal stress and the normal stress induced by the interlayer constraint (as shown

FIGURE 1: The occurrence condition of the coal seam in the weakly cemented soft rock strata.

FIGURE 2: The microelement model of rock-coal body.

FIGURE 3: The stress decomposition diagram for the analysis model.

in Figure 4). According to the superposition principle, the following is obtained:

$$\begin{aligned}
 \sigma_y^r &= \sigma_y, \\
 \sigma_y^m &= \sigma_y \\
 \sigma_x^r &= \sigma_x + \sigma_{xp}^r, \\
 \sigma_x^m &= \sigma_x + \sigma_{xp}^m
 \end{aligned} \tag{1}$$

where the superscripts r and m represent the soft rock and coal body, respectively, and the subscript p represents the induced stress resulting from the constraint between layers.

As shown in Figure 5(a), with the independent effect of σ_y , the soft rock and coal body are extended outward laterally. The tensile strain of the coal body in x direction is $\varepsilon_x^m(y)$, and that of soft rock is $\varepsilon_x^r(y)$, where x represents the direction of the normal stress. Because $E_r > E_m$ and $\nu_r < \nu_m$, the relation between the lateral strains of the coal body and rock formation is $\varepsilon_x^r(y) < \varepsilon_x^m(y)$. Due to the interface adhesion and there being no mutual slide, the lateral strain of the coal body and rock formation for keeping the lateral strain coordination on the interface is $\varepsilon_x(y)$. Therefore, under the effect of σ_y , a compressive stress $\sigma_{xp}^m(y)$ of the coal seam in x direction is induced on the interface, and a tensile stress $\sigma_{xp}^r(y)$ is induced in the soft rock. According to the static, $\sigma_{xp}^m(y) = \sigma_{xp}^r(y)$ are obtained, which are both signed as $\sigma_{xp}(y)$.

As shown in Figure 5(b), with the independent effect of σ_x , the compressive strain of the soft rock and coal body in x direction is $\varepsilon_x^m(x)$ and $\varepsilon_x^r(x)$, and $\varepsilon_x^m(x) > \varepsilon_x^r(x)$. Due to the adhesion constraint, the coordinated lateral strain in x direction is $\varepsilon_x(x)$. The tensile stress $\sigma_{xp}^m(x)$ is induced in the coal seam, and the compressive stress $\sigma_{xp}^r(x)$ is induced in the rock formation. According to the static, $\sigma_{xp}^m(x) = \sigma_{xp}^r(x)$ are obtained, which are both signed as $\sigma_{xp}(x)$.

According to the above analysis, under the independent effect of normal stress, the normal stress in a coal seam and rock formation is generated in other directions, changing the stress state nearby. With the independent effect of each normal stress, the following geometric relationship of the deformation is obtained:

$$\begin{aligned}
 \varepsilon_x^r(y) &= \varepsilon_x^m(y) = \varepsilon_x(y) \\
 \varepsilon_x^r(x) &= \varepsilon_x^m(x) = \varepsilon_x(x)
 \end{aligned} \tag{2}$$

FIGURE 4: The normal stress distribution of the analysis model.

FIGURE 5: The transverse strain relationship near the contact interface under normal stress.

Using the generalized Hooke law, the above equations are resolved to obtain the induced normal stress:

$$\begin{aligned}\sigma_{xp}(y) &= \frac{\alpha - \beta}{\alpha + 1} \nu_m \sigma_y \\ \sigma_{xp}(x) &= \frac{\alpha - 1}{\alpha + 1} \sigma_x\end{aligned}\quad (3)$$

By substituting (3) with (1), the normal stress of the micro-bodies in the coal seam and rock near the interface of the coal seam-rock formation is expressed as

$$\begin{aligned}\sigma_y^r &= \sigma_y, \\ \sigma_y^m &= \sigma_y, \\ \sigma_x^r &= a_1 \sigma_x - a_3 \sigma_y \\ \sigma_x^m &= a_2 \sigma_x + a_3 \sigma_y\end{aligned}\quad (4)$$

where

$$\begin{aligned}a_1 &= \frac{2\alpha}{\alpha + 1}, \\ a_2 &= \frac{2}{\alpha + 1}, \\ a_3 &= \frac{\alpha - \beta}{\alpha + 1} \nu_m\end{aligned}\quad (5)$$

Due to the neglect of anisotropy in the coal seam and rock formation, the shear stress is induced only from

circumstances related to a lateral deformation of the interface under the independent effect of shear stress in Figure 3(b). Namely, any other shear stress is not induced from τ_{xy} and τ_{yx} . To sum up, the adhesion constraint effect on the coal seam-rock's interface results in a variation of the stress state in the coal seam and rock, and the strain is coordinated on the coal seam-rock's interface. However, due to the difference of coal or rock mass's material property, the stress of a part of coal or rock mass is not continuous. If $\alpha = \beta = 1$, i.e., the same material property in the coal seam-rock's complex, the induced stress is not generated on the coal seam-rock's interface.

3. The Calculation of the Coal Side Limit Equilibrium Zone Width in a Thick Coal Seam

3.1. The Calculation Model. The coal series in the weakly cemented soft rock in western China is dominated by coal seams of medium thickness, or those that are very thick, and the rock formation is characterized by low strength, poor cementation, and unstable mechanical properties. Thus, the roadway is mostly excavated in the coal seam, forming a typical full coal roadway. After excavating the coal seam, the coal side's entity stays in a state of stress equilibrium, and the coal side is extruded by the roof and floor along the roadway. The accompanying shear stress is generated on the interfaces between the coal side and coal seam's roof and floor. A calculation model is established, as shown in

Figure 6, with the coal side midpoint as the origin of the coordinates, the x -axis along the coal side's midcourt line, ABCD as the stress limit equilibrium zone, x_p as the width of the limit equilibrium zone, p_x as the constraint resistance of the supporting structure of the coal side, and σ_x as the coal seam's horizontal stress at $x = x_p$.

In order to apply the loose medium limit equilibrium theory optimally, the following assumptions are made in the calculation model:

- (1) The coal side is an ideal elastic body.
- (2) The coal side is only influenced by its gravity, and not by the horizontal tectonic stress.
- (3) The stress of the coal side is symmetrized against the coal pillar's neutral plane.
- (4) The failure occurs in the coal side due to the yield and shear stress, and the interfaces between the coal side and coal seam's roof and floor are yield surfaces due to the coal side's motion against the roof and floor. The normal stress and shear stress in the slip plane meet the conditions of the limit equilibrium.

3.2. A Stress Analysis in the Limit Equilibrium Zone. According to the above assumptions, and when the body force is neglected, the coal stress in the area near the interface is expressed by the following stress differential equilibrium equation:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \quad (6)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} = 0 \quad (7)$$

The shear slip plane stress meets the following equilibrium conditions [31]:

$$\tau_{xy} = -(\sigma_y \tan \varphi + C) \quad (8)$$

where C and φ represent the cohesive force and frictional angle of coal seam, respectively.

By substituting (7) with (8), we obtain

$$\begin{aligned} \sigma_y &= A'_1 A'_2 e^{A(h/2)} e^{(A/tg\varphi)x} + A_1 \\ \tau_{xy} &= -[(A'_1 A'_2 e^{A(h/2)} e^{(A/tg\varphi)x} + A_1) tg\varphi + C] \end{aligned} \quad (9)$$

where A, A_1, A'_1, A'_2 are undefined constants.

We then define

$$A_0 = A'_1 A'_2 e^{Ah/2} \quad (10)$$

Then, (9) is expressed as

$$\begin{aligned} \sigma_y &= A_0 e^{A/tg\varphi x} + A_1 \\ \tau_{xy} &= -[(A_0 e^{A/tg\varphi x} + A_1) tg\varphi + C] \end{aligned} \quad (11)$$

FIGURE 6: Calculation model of stress limit equilibrium in coal seam.

It can be seen that the expression of stress is only resolved by determining the undefined constants A, A_1 , and A_0 .

The stress limit equilibrium zone should meet the following conditions:

- (1) The whole coal side's stress limit equilibrium zone, ABCD, should meet the requirements of $\sum F_x = 0$; namely,

$$h[\sigma_x]_{x=x_p} + 2 \int_0^{x_p} [\tau_{xy}] dx - p_x h = 0 \quad (12)$$

- (2) At the boundary of the limit equilibrium zone, the vertical stress should meet [32]

$$[\sigma_y]_{x=x_p} = k_x \gamma H \quad (13)$$

$$k_x = 1 + k_0 e^{-bx}$$

where k_0, b are coefficients related to elastic modulus of coal seams and gangue, k_x is the stress concentration coefficient, H the buried depth, and γ the gravity.

- (3) At the limit equilibrium zone's boundary, where the coupling of the rock-coal's seam occurs, the horizontal stress is expressed as

$$[\sigma_x]_{x=x_p} = a_2 \sigma_x + a_3 \sigma_y = (a_2 \lambda + a_3) [\sigma_y]_{x=x_p} \quad (14)$$

By substituting (12) with (8) and (14), we obtain

$$h(a_2 \lambda + a_3) \frac{d[\sigma_y]_{x=x_p}}{dx_p} - 2tg\varphi [\sigma_y]_{x=x_p} - 2C = 0 \quad (15)$$

By resolving the formula we obtain

$$[\sigma_y]_{x=x_p} = A'_0 e^{(2tg\varphi/h(a_2 \lambda + a_3))x_p} - \frac{C}{tg\varphi} \quad (16)$$

By defining $x=x_p$ in (11), and making a comparison with (16), we obtain

$$\begin{aligned} A &= \frac{2tg^2\varphi}{h(a_2 \lambda + a_3)}, \\ A_1 &= -\frac{C}{tg\varphi}, \\ A_0 &= A'_0 \end{aligned} \quad (17)$$

TABLE 1: Physical-mechanical parameters of weak soft rock in western China.

Rock layer	Seam thickness h/m	Strength of coal seam		Deformation parameters of coal-rock body		Lateral coefficient λ	Supporting strength p_x/MPa
		C/MPa	$\phi/^\circ$	α	β		
unstable	8	1	15	0.7	0.5	0.6	0.05
relatively stable	6	3	24	1.5	0.7	0.5	0.10
stable	4	5	35	2	0.8	0.4	0.25

Here, only A_0 is not worked out. According to (12)-(14), we obtain

$$A_0 e^{(2tg\phi/h(a_2\lambda+a_3))x_p} - \frac{C}{tg\phi} = k\gamma H \quad (18)$$

$$2 \int_0^{x_p} [\tau_{xy}] dx + h(a_2\lambda + a_3)k\gamma H - p_x m = 0$$

According to (11), we obtain

$$\int_0^{x_p} [\tau_{xy}] dx = \frac{A_0 h(a_2\lambda + a_3)}{2} (1 - e^{(2tg\phi_p/h(a_2\lambda+a_3))x_p}) \quad (19)$$

There are unknown variables A_0 and x_p in (18). By substituting (18) with (19), and combining the formulas, we obtain

$$A_0 = \frac{C}{tg\phi} + \frac{p_x}{(a_2\lambda + a_3)} \quad (20)$$

The stress limit equilibrium zone width x_p is expressed as

$$x_p = \frac{h(a_2\lambda + a_3)}{2tg\phi} \ln \left(\frac{k\gamma H + C/tg\phi}{C/tg\phi + p_x/(a_2\lambda + a_3)} \right) \quad (21)$$

By substituting (11) with (17) and (20), the stress of the coal's interface inside the coal stress's limit equilibrium zone is expressed as

$$\sigma_y = \left(\frac{C}{tg\phi} + \frac{p_x}{a_2\lambda + a_3} \right) e^{(2tg\phi/h(a_2\lambda+a_3))x} - \frac{C}{tg\phi} \quad (22)$$

$$\tau_{xy} = - \left(C + \frac{p_x tg\phi}{a_2\lambda + a_3} \right) e^{(2tg\phi/h(a_2\lambda+a_3))x}$$

3.3. An Analysis of Factors Influencing the Limit Equilibrium Zone Width. According to (21) and (22), not only are the stress's limit equilibrium zone width and stress state of the coal side related to the buried depth of the roadway H , excavated coal seam thickness h , coal seam strength parameter ϕ and C , coal side stress concentration factor k , horizontal lateral pressure coefficient λ , and supporting strength of the roadway's side p_x , but they also have an effect on the deformation parameter of the rock and coal seam, which is due to the coupling effect of the rock-coal's seam.

We now define the stress concentration factor $k=2$, overlying rock formation gravity $\gamma=18 \text{ kN/m}^3$, coal seam Poisson's ratio $\nu_m=0.32$, and buried depth $H=100\text{-}500 \text{ m}$. According to the geological exploration data of weakly cemented soft rock, the limit equilibrium zone width is analyzed using three groups of parameters, as seen in Table 1 [3, 4, 32].

3.3.1. The Influence of the Roadway's Buried Depth. The coal side's limit equilibrium zone width versus the roadway's buried depth with the three groups of formation parameters listed in Table 1 is displayed in Figure 7. According to (21), x_p increases regularly in a logarithm relation as the buried depth increases. In the stable rock formation, x_p basically remains unchanged as the buried depth changes within $H=400\text{-}500 \text{ m}$. In the relatively stable rock formation, x_p increases by only a small amount. In the unstable rock formation, x_p increases sharply as the buried depth increases. Within 500 m of the buried depth, there is a big difference in the limit equilibrium zone of various rock formations. In the stable rock formation the coal side's limit equilibrium width is $x_p \leq 1.32 \text{ m}$, in the relatively stable rock formation it is $x_p \leq 4.3 \text{ m}$, and in the unstable rock formation the maximum x_p reaches as high as 19.35 m.

3.3.2. The Influence of the Coal Seam's Strength Parameters. Assuming the buried depth $H=400 \text{ m}$, and keeping the relatively stable surrounding rock parameters as the basic parameters, and other parameters unchanged, the variation of the limit equilibrium zone width x_p can be analyzed.

The vertical stress versus the coal seam's cohesive force C near the coal seam's shear interface is displayed in Figure 8. The stress expressed with a dashed line is $\sigma_{\text{crit}}=k\gamma H$, and is the vertical stress on the interface between the stress's limit equilibrium zone and elastic region, as shown in Figure 6. The symbols in the following figures have the same meanings. The horizontal axis value of the intersectional point of the vertical stress curve and σ_{crit} curve under a different cohesive force corresponds to the limit equilibrium zone width. Thus, as the coal seam's adhesive force increases, the vertical stress of the coal seam yield's interface increases, and the width of the corresponding limit equilibrium zone decreases.

The vertical stress in the coal seam versus the coal seam's frictional angle on the coal seam's interface is displayed in Figure 9. As the frictional angle increases, the vertical stress on the interface increases noticeably, with an increasing growth range, and the limit equilibrium zone width decreases

FIGURE 7: Relationship between width of limiting equilibrium zone and buried depth.

FIGURE 8: Relationship between vertical stress and cohesion of coal seam near the interface.

correspondingly. According to Figures 8 and 9, the strength parameters of the coal body near the coal seam-rock formation's interface have a large influence on the width and vertical stress distribution of the limit equilibrium zone. According to Section 2, the coupling effect of the rock formation-coal's seam changes the stress state of the coal seam near the interface and also has an influence on the coal seam's strength, which has been illustrated in previous research [33, 34].

3.3.3. The Influence of the Coal Seam's Thickness. The influence of the coal seam's thickness on the stress distribution on

FIGURE 9: Relationship between vertical stress and frictional angle of coal seam near the interface.

FIGURE 10: Relationship between vertical stress and depth of coal seam.

the coal seam's interface is analyzed using the basic parameters of a relatively stable rock formation. The distribution of vertical stress on the coal seam's interface with different coal seam thicknesses is shown in Figure 10. Obviously, with a thin coal seam, the vertical stress on the coal seam's interface changes abruptly, and the limit equilibrium zone has a small width. As the coal seam thickens, the vertical stress on the coal seam's interface increases at a slower rate, and the limit equilibrium zone is widened noticeably; e.g., when the coal seam thickness $h=4$ m, the x_p is 2.48 m, but when it is $h=7.5$ m, x_p increases to 4.69 m. Thus, in a coal seam of medium thickness or that which is very thick, in the weakly cemented soft rock formation with a low strength in western China, supporting measures are needed to ensure the stability of the roadway.

3.3.4. The Influence of the Coupling Effect of the Rock-Coal's Seam. Due to the relatively stable basic parameters of the

FIGURE 11: Relationship between width of limiting equilibrium zone and stiffness ratio.

rock, the influence of the coupling effect of the rock-coal's seam on the limit equilibrium zone width is analyzed using the varying rock-coal seam stiffness ratio α and transverse deformation factor β . After excavating the roadway, the roof-coal seam-floor constitutes a composite loading system, and the coal side's stability should be related to the comprehensive effect of different geological bodies. According to (16), the limit equilibrium zone width is closely related to the deformation parameters of the coal seam and rock formation. The limit equilibrium zone width x_p versus the stiffness ratio α is shown in Figure 11. As the ratio of the elasticity modulus of the roof rock formation and coal seam increases, x_p decreases noticeably with nonlinearity. On the one hand, if the coal seam's stiffness remains unchanged, an increment of the rock formation's stiffness will strengthen the bearing capacity of the roof and reduce the action force on the coal seam. On the other hand, according to (4), an increment of induced stress in the coal seam near the interface will decrease the limit equilibrium zone width. The relationship between the limit equilibrium zone width x_p and the ratio of transverse deformation factor of the rock-coal's seam is shown in Figure 12. As Poisson's ratio influences the induced stress of the coal seam near the interface and causes an increment of the transverse deformation factor, x_p decreases linearly.

3.3.5. The Influence of the Supporting Strength. Using the unstable rock formation parameters as basic parameters, the influence of the supporting strength on the width and vertical stress distribution of the limit equilibrium zone is analyzed.

The vertical stress on the coal seam's interface versus the coal side's supporting strength under different coal seam strengths is shown in Figure 13. With a low coal seam strength, e.g., the cohesive force $C=1$ MPa in Figure 13(a), an increment of supporting strength will reduce the limit equilibrium zone width, and the supporting strength will have a large influence on the roadway's stability. When $C=3$ MPa in Figure 13(b), an increment of supporting strength will have little influence on reducing the limit equilibrium zone. Thus,

FIGURE 12: Relationship between width of limiting equilibrium zone and transverse deformation factor between rock and coal.

in a soft low-strength coal seam, an increment of supporting strength will clearly decrease the coal side's failure zone width.

3.4. A Discussion about the Model. The formula for calculating the stress limit equilibrium zone width established by Hou and Ma [29] using the loose medium limit equilibrium theory has been widely applied in various scientific research and engineering projects [35–37]. The formula is expressed as

$$x_0 = \frac{mA}{2tg\varphi_0} \ln \left(\frac{k\gamma H + C_0/tg\varphi_0}{C_0/tg\varphi_0 + P_x/A} \right) \quad (23)$$

where x_0 is the width of the limit equilibrium zone, A is the lateral pressure coefficient, m is the coal seam thickness, k is the stress concentration factor, γ is the rock formation gravity, H is the buried depth, P_x is the supporting resistance, and C_0 and φ_0 correspond to the cohesive force and frictional angle of the rock-coal seam's interface, respectively.

With the parameters of a relatively stable rock formation, the differences of the model presented in this paper and (23) are compared. If $\alpha=\beta=1$, (21) is simplified to (23). The limit equilibrium zone width versus the coal seam's cohesive force under different rigidities is shown in Figure 14. If $\alpha=1$, the same result is obtained from the model presented in this paper and (23). As the cohesive force increases, the limit equilibrium zone width decreases significantly. With the same cohesive force, as α increases the limit equilibrium zone width x_p decreases noticeably. With different values of A , the tendency of an x_p variation versus the cohesive force C is identical. The superiority of the model presented in this paper lies in its consideration of the coupling effect of the rock formation-coal's seam, which is due to the interface adhesion.

When deriving (21), it is assumed that the shear failure occurs along the interfaces between the coal side and the roof and floor's coal seam. Thus, C and ϕ represent the adhesive force and frictional angle of the coal seam, respectively. Thus, the formula presented in this paper is applicable in following conditions:

FIGURE 13: Relationship between vertical stress and supporting strength.

FIGURE 14: Calculation results comparison between our model and Hou [29] ($\beta=1$).

- (1) A not completely excavated coal seam of medium thickness or that which is very thick, where the coal side is connected wholly with the roof or floor;
- (2) A completely excavated coal seam of medium thickness, or that which is very thick, where the interfaces between the coal side and the roof and floor's coal seam have a high adhesion strength, and the failure of the coal side occurs along the rock-coal seam's interface;
- (3) If the failure occurs along the rock-coal seam's interface and C and ϕ are replaced with interface strength parameters.

4. Engineering Application

In order to validate the practical application value of the proposed method for calculating the limit equilibrium zone width of the coal side, it is analyzed using engineering examples from previous study [29]. The Quantai, Qishan, and Dongzhuang Mines are typical coal seams with a "soft roof, floor, and coal seam." The mining roadway is characterized by a large cross section, deep buried depth, complicated surrounding rock geological conditions, and small coal pillars, and it is classified as an extremely unstable mining roadway according to the "Classification Scheme of the Stability of the Surrounding Rock in the Mining Roadway." It is difficult to maintain the roadway. The ratio of the rigidity of the roof and floor rock formations and coal seam is $\alpha=1.5-3$, the ratio of lateral deformation coefficients is $\beta=0.7-0.8$, Poisson's ratio of the coal seam is $\nu_m=0.3$, and the other parameters are shown in Table 2.

In this example, different limit equilibrium zone widths are obtained using different calculation methods. As shown in Table 3, although the results from the three methods are more consistent with the actual measurement results, there are still some differences. The result calculated by Hou and Ma [29] based on (23) is a constant. The roadway equilibrium width from Liu et al. [30] consists of a range of values, which is based on (23), and the advantage lies in considering the integrity of the rock body whilst avoiding the difficulty in determining the mechanical parameters of the roadway's glide plane strength. However, the method is based on the geological mechanical conditions of the coal seam. In the model presented in this paper, the integral bearing characteristics of the roof-coal seam-floor are considered, and the limit equilibrium zone width varies within the range of α and β . The actual result is in the variation range. Thus, the method for calculating the roadway's limit equilibrium zone width in this paper is more applicable and feasible.

TABLE 2: Calculation parameters of roadway.

Parameters	Depth H/m	Density $\gamma \text{ kN/m}^3$	Thickness h/m	Stress con- centration factor k	Lateral coefficient λ	Cohesion C/MPa	Friction $\phi/^\circ$	Support pressure p_x/MPa
value	470	25	3	2	0.4	0.0392	28	0.214 (Annular support) 0.056 (Arched support)

TABLE 3: The width of limit equilibrium zone under different support styles.

Support form	Calculation results by our model/m			Hou and Ma [29]	Liu et al [30]	Measured results
	α	$\beta=0.7$	$\beta=0.8$			
Unsupported	1.5	6.78	6.57	6. 23	4. 83~6. 41	No results
	2	6.45	6.29			
	2.5	6.22	6.08			
	3	6.06	5.93			
Annular support	1.5	4.33	4.18	3. 78	2. 51~3. 92	3
	2	4.08	3.95			
	2.5	3.90	3.79			
	3	3.75	3.68			
Arched support	1.5	5.54	5.36	4. 95	3. 52~5. 01	4~ 5
	2	5.26	5.10			
	2.5	5.04	4.91			
	3	4.89	4.78			

5. Conclusions

In this paper, starting from the structural effect of the roadway’s roof-coal seam-floor, we analyzed the mechanism of stress transfer on the rock-coal seam’s interface, deduced the formula for calculating the width and stress distribution of the coal side’s equilibrium zone under the coupling effect of the rock-coal’s seam, and validated the effectiveness of the model through a comparison with previous research results and practical engineering examples. The main conclusions of this study are as follows:

- (1) If the adhesion strength of the rock formation-coal seam’s interface is higher than that of the coal seam, a failure of the coal side will occur along the coal seam. Due to the interface constraint effect, the strain is consistent on the rock-coal seam’s interface, resulting in the induced stress and abrupt change of the stress state in the rock formation and coal seam around the interface. The induced stress is related to the ratio of the rigidity of the rock formation and coal seam and that of the lateral deformation coefficient; i.e., there is a coupling effect of the rock formation and coal seam.
- (2) The model based on the loose medium limit equilibrium theory, taking into consideration the coupling effect of the rock-coal’s seam, shows that the width and stress state of the coal side’s stress limit equilibrium not only are related to the roadway’s buried depth, excavated coal seam thickness, coal

seam strength parameter, roadway stress concentration factor, horizontal lateral pressure coefficient, and roadway side’s supporting strength but also have an effect on the deformation parameter of the rock and coal seam. A high ratio of the roof-coal seam rigidity results in a smaller limit equilibrium zone width.

- (3) A comparison of previous research results and measured values shows that the expression of the limit equilibrium zone width is more applicable; with the comprehensive structural effect of the roof-coal seam-floor also being considered.

Data Availability

The calculation data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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