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Published in:
International Journal of Mining Science and Technology

Published: 01/03/2019

Document Version:
Final Published version, also known as Publisher’s PDF, Publisher’s Final version or Version of Record

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Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1016/j.ijmst.2018.04.006

Publication details:

Citing this paper
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Download date: 11/03/2020
Strength criterion effect of the translator and destabilization model of gas-bearing coal seam

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A B S T R A C T

Coal seam destabilization inflicts damage to equipment, causes property loss and personnel casualties, and severely threatens mining safety and efficient production. To further understand this destabilization based on the basic theory of Lippmann seam destabilization, a mathematical model was introduced for gas pressure distribution by considering intermediate principal stress and support resistance. Subsequently, we established a translation model suitable for the entire roadway coal seam with rocky roof and floor by applying the unified form of yield criterion in the state of plane strain. We also obtained the analytic expressions of coal seam stress distribution on both sides of the roadway and the widths of plastic and disturbance zones. Afterward, we analyzed several typical cases with different material yield criteria, obtained the plastic zone widths of the coal seam under different gas pressures, and assessed the effects of support resistance, roadway size, and coal strength on coal seam destabilization. Results showed that: the results obtained on the basis of Wilson and Mohr–Coulomb criteria are considerably conservative, and the use of Druker–Prager criteria to evaluate the rockburst-induced coal seam destabilization is safer than the use of the two other criteria; coal seam stability is correlated with gas pressure, and high-pressure gas accelerates the coal seam destabilization.

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1. Introduction

The dynamic destabilization of coal seams in coal mining is a frequently occurring disaster accompanied with a sudden force transfer and violent energy release. Without prevention and control, this destabilization will inflict equipment damage, roadway collapse, and personnel casualty, thereby severely threatening coal mine production and safety. During the 20th century, researchers made some progress by studying the mechanisms of coal seam dynamic destabilization related to rockburst [1]. Most previous studies ignored the effect of gas during roadway rockburst-induced coal seam destabilization. The microseismic field, gas monitoring, and theoretical analysis showed that gas may be an important factor causing dynamic instability [2–8]. Therefore, the effect of gas should be considered in the study of coal seam impingement mechanism.

Coal-seam-translation-rockburst destabilization is a typical coal/rockburst destabilization. Lippmann et al. [9–11] proposed a coal-seam-translation-rockburst destabilization theory using the Mohr–Coulomb (M–C) criterion from the structure destabilization concept perspective and by only considering the interaction between the coal seam and its roof and floor. Jiang et al. introduced the fractional resistance inside the coal seam and applied the M–C criterion to establish their mechanic model for coal-seam-translation-rockburst destabilization, and found the index for measuring the extent of the entire roadway outburst based on their analyses on the pre-outburst of critical stress distribution in the coal seam and the characteristics of 3D model-related geometric parameters [12]. Zhu et al. considered the effects of yield criterion, roadway size, and other factors on coal-seam-translation outbursts and applied the Hoek-Brown strength theory to improve Lippmann’s coal seam translation outburst model [13–15]. The effect of gas on ground pressure impact was investigated, and the coal translator bump model of linearly distributed gas was subsequently established on the basis of M–C criteria. According to these studies of the dynamic destabilization mechanism induced by roadway rockburst, the M–C and Wilson criteria are mostly

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used to evaluate the coal seam rockburst; however, both of these criteria ignore the role of intermediate principal stress [16]. The Druker–Prager (D–P) criterion, which is based on the M–C criterion, is commonly used as the material yield criterion of roadway impulse dynamic instability to study the effect of intermediate principal stress and hydrostatic pressure. The D–P criterion is also usually used to fit the M–C criterion in engineering calculation. Jiang et al. used the D–P criterion to obtain the coal seam rockburst and instability model, but ignored the possible effect of gas on the width of the plastic zone in the coal wall [17,18]. On the basis of Wilson criterion, Wang et al. improved the yield bandwidth and stability formulas of the thick-strip coal pillar by experimental analysis, but the effect of the principal stress on the stability of the coal pillar is not considered [19].

The main stress is a considerably important influencing factor in the study of strength criterion on the translator bump model of coal seam; nevertheless, the M–C and Wilson criteria are not considered when the role of the main stress is determined [20]. To explore the applicability of these three commonly used strength criteria in the translational instability problem of gas-bearing coal seam, the present study analyzes the unified form of these criteria in the plane strain state, on the basis of Lippmann theory. The middle principal stress and the support resistance are both considered by changing the boundary condition and replacing the yield criterion. This study also considers the gas–solid coupling method to establish the translator bump model of gas-containing coal seam, analyze the stress distribution of the whole coal seam prior to destabilization and the distribution of plastic and disturbance zones widths, and apply the coal seam stress distribution curves through an actual case. Finally, we utilize the constructed model to examine the effects of gas, roadway width and height, support resistance-coal strength (internal friction angle), and support resistance-underground stress on the process of coal seam destabilization and failure.

2. Coal seam destabilization model with consideration of gas effect

2.1. Analysis of coal seam destabilization mechanism

We assume that a horizontal seam with a thickness of 2 h is subject to the uniform vertical stress q, horizontal stress λq (where λ is the lateral pressure coefficient), seam gas pressure p and roadway width 2b. When the roadway is excavated, the stress in a certain coal zone along both sides of the roadway will be redistributed. The affected region is called the disturbance zone with length l, as shown in Fig. 1, where the plastic, elastic, and initial stress zones are marked as I, II and III, respectively; xp is the width of the plastic zone; pr is the support resistance in front of coal seam; and σx, σy and σz are the stresses in vertical and horizontal directions in coal mass, respectively.

For convenience, the following mechanical assumptions are established: (1) the support resistance pr is evenly distributed along the excavation face; (2) the roof and floor of coal seam are rigid bodies with the same sliding resistance, and the coal mass is a homogeneous, isotropic, and elastic–plastic material; (3) the problem after ignoring the thin-plate bending effect is reduced as the plane strain problem; (4) the coal seam in the elastic zone satisfies Hooke’s law; and (5) the slip friction on the interface between coal and rock satisfies Eq. (1).

\[
\tau_c = c + \sigma_y \tan \varphi \quad (1)
\]

where \(\tau_c\) is the cohesion on the coal–rock interface, MPa; \(\varphi\) the friction angle on the coal–rock interface; \(\sigma_y\) the stress of the seam in the vertical direction, MPa.

2.2. Mechanical model

A microvolume element with height 2h extracted from the coal mass on the roadway side is used for mechanical analysis. The applied loads include horizontal stress, pore pressure, and friction resistances on the interfaces between the seam and its roof and floor, as shown in Fig. 2. According to the mechanical equilibrium conditions, the balance equation of forces on the microelement is formed.

\[
\frac{\partial \sigma_x}{\partial x} + \tau_c = 0 \quad (2)
\]

where \(\tau_c\) is the Coal-rock interface friction resistance; and \(\sigma_x\) is the Coal seam horizontal stress, MPa.

The disturbance zone contains the elastic and plastic zones. In the elastic zone, coal seam satisfies the following elastic constitutive equation:

\[
\frac{\sigma_{se}}{\sigma_{st}} = \frac{1 - \mu}{\mu} \quad \tau_c = c + \sigma_y \tan \varphi \quad (3)
\]

where \(\mu\) is the Poisson’s ratio of the coal mass.

After the roadway excavation, the load applied by the coal mass along the original roadway is transferred onto the vicinal coal mass, and it satisfies the following integral equation:

\[
bq = \int_0^l (\sigma_y - q)dx \quad (4)
\]

With the following boundary conditions:

\[
\begin{align}
\sigma_x^l &= p_r, \quad p = p_0(x = 0) \\
\sigma_x^I &= \sigma_y^I, \quad \sigma_y^I = \sigma_y^l(x = x_p) \\
\sigma_x^I &= \sigma_y^I, \quad p = p_l(x = L)
\end{align} \quad (5)
\]
where I, II, and III are the plastic, elastic, and initial stress zones, respectively; \( p_i \) the original gas pressure, MPa; and \( p_0 \) is the roadway gas pressure, MPa.

### 2.3. Three strength criteria

The criterion that is used most extensively in rock (soil) engineering is the M–C criterion, which is expressed as follows:

\[
\sigma_{ye} = \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_{se} + \frac{2\cos \varphi}{1 - \sin \varphi}. \tag{6}
\]

Wilson criterion, which does not consider the effect of the principal stress, is expressed as follows:

\[
\sigma_{ye} = 4\sigma_{se}. \tag{7}
\]

The circumscribed D–P criterion is the elastoplastic material strength criterion proposed by Drucker and Prager and expressed as follows:

\[
\sigma_{ye} = \frac{1 + 3\eta}{1 - 3\eta} \sigma_{se} + \frac{2k}{1 - 3\eta} \eta = \frac{2\sin \varphi}{\sqrt{3(3 - \sin \varphi)}} k = \frac{6\cos \varphi}{\sqrt{3(3 - \sin \varphi)}} \tag{8}
\]

where \( \sigma_{se} \) and \( \sigma_{ye} \) are the effective stresses of the coal seam in the horizontal and vertical directions, MPa, respectively; \( c \) the coal seam cohesion, MPa; and \( \varphi \) the coal seam internal friction angle, \(^\circ\).

Comprehensive comparison of Eqs. (6)–(8) demonstrated that in the plane strain state, these three different strength criteria can be written as follows:

\[
\sigma_{ye} = H\sigma_{se} + l \tag{9}
\]

where \( H \) is the mono-parameter function of the internal friction angle; and \( l \) the bi-parameter function of both the cohesion and internal friction angles. Thus, Eq. (9) can be used to establish the translation outburst model of coal seam.

### 2.4. Gas pressure distribution characteristics

Terzaghi defined the effective stress as the total stress minus the fluid stress and proposed an effective stress principle for unsaturated soil [21]. According to this principle, Schmit and Zoback introduced the effective stress coefficient and obtained a largely general effective stress principle [22]. Applying this principle to the gas-bearing coal mass determines the relationship of the total stress to the gas pressure and the effective stress of gas-bearing coal mass:

\[
\sigma_m = \sigma_{se} + x p e_m \tag{10}
\]

where \( \sigma_m \) is the whole stress, MPa; \( \sigma_{se} \) the effective stress, MPa; \( x \) the effective stress coefficient; \( e_m \) the Kronecker symbol; and \( p \) the coal seam’s pore pressure (gas pressure), MPa.

The characteristics of gas pressure occurrence in different coal mines or coal seams of similar coal mine are inconsistent. Even for the same coal seam, with the constant advancement of roadway excavation, the gas is consecutively released, and the gas pressure distribution in the coal seam also dynamically changes [23]. We assume that the gas pressure can be described using the following equation:

\[
p = a(1 - e^{-x/0.1l}) \tag{11}
\]

where \( p \) is the gas pressure, MPa; \( a = p_i \) the original gas pressure, MPa; \( L \) the width of the disturbance zone, m; and \( x \) the distance from the coal wall of the roadway side, m.

The rationality of Eq. (11) is verified using the measured gas pressure on the roadway side [24]. The fitting curve shown in Fig. 3 presents \( R^2 = 0.9863 \), thereby indicating that Eq. (11) is a suitable function to express gas pressure distribution.

### 3. Determinations of coal seam stress distribution states and their distribution zone ranges

3.1. Calculation of coal seam stresses

(1) Distribution of stress in the initial stress zone \((x > L)\):

\[
\sigma_{se}^1 = i q, \sigma_{ye}^1 = q, p = p_i. \tag{12}
\]

(2) Distribution of stress in the elastic zone \((x_p < x < L)\): Jointly solving Eqs. (1), (2), (3), (10), and (11) results in the following equations.

\[
\sigma_{se}^2 = \frac{Ae^{x/(1 - \mu)} - c_L (1 - \mu) p_L}{\mu \tan \varphi_L} + \frac{x \tan \varphi_L (1 - 2\mu) p_L}{10h(1 - \mu) + L\mu \tan \varphi_L} e^{-x/(0.1l)}. \tag{13}
\]

Additionally, the use of boundary conditions in Eq. (5c) into Eq. (13) obtains the following equation:

\[
A = \left(i q, \frac{c_L (1 - \mu)}{\mu \tan \varphi_L} + \frac{x (1 - 2\mu) p_L}{10h(1 - \mu) + L\mu \tan \varphi_L} e^{-x/0.1l}\right) e^{-x/(1 - \mu)}. \tag{14}
\]

The stress distribution in the elastic zone obeys the following equation:

\[
\sigma_{se}^3 = \frac{[\sigma_{se}^2 - \mu p_i (1 - e^{-x/0.1l})] \mu}{1 - \mu} + \frac{x p_i (1 - e^{-x/0.1l})}{10h + \mu \tan \varphi_L} e^{-x/0.1l} \tag{15}
\]

(3) Distribution of stress in the plastic zone \((x < x_p)\):

Solving Eqs. (1), (2), (9), (10), and (11) together results in the following equation:

\[
\frac{\partial \sigma_x}{\partial x} \tan \varphi_L H/\mu \sigma_x = \left[(1 - H) x p_L + I \right] \tan \varphi_L + c_L \tag{16}
\]

Solving the resulting one-order linear differential equation obtains the following equation:

\[
\sigma_x^p = \frac{C e^{x/(1 - \mu)} - c_L \tan \varphi_L H}{\mu} \tan \varphi_L (1 - H) x p_L + I \cdot 10h + \tan \varphi_L H e^{-x/0.1l} \tag{17}
\]
The use of boundary condition of Eq. (5a) into Eq. (16) results in the following relation:

\[ C = p_i + \frac{c_t}{\tan \phi_c} \left( \frac{1 - H \tan \phi_p}{H} + \frac{1 - H \tan \phi_p L}{10H + \tan \phi_p H L} \right. \]

Therefore, the characteristics of vertical stress distribution in the plastic zone can be expressed as follows:

\[ \sigma_y = H(\sigma_y' - \frac{1}{10} + 1 - e^{-0.1}) + I + \sigma_p(1 - e^{-0.1}) \]

3.2. Determination of disturbance and plastic zones widths

Substituting Eqs. (1) into (2) results in the following equation.

\[ \frac{\partial \sigma_y}{\partial x} = \frac{c_t + \sigma_y \tan \phi_c}{h} \]

Subsequently, solving Eqs. (4) and (18) obtains the following equation.

\[ L = \frac{h \sigma_y(L) \cot \phi_c - h \sigma_y(0) \cot \phi_c - b q}{q + c_t \cot \phi_c} \]

Substituting the boundary conditions in Eqs. (5a) and (5c) into (19) results in the following equation.

\[ L = \frac{h(\lambda - \frac{b}{q} \frac{1}{c_t} \tan \phi_c)}{\tan \phi_c + \frac{b}{q}} \]

According to Eq. (20), the width of the disturbance zone is clearly due to coal mining, which is related to the interface parameters (friction angle and cohesion), the lateral pressure coefficient, and the buried depth and size of the roadway.

Combining Eqs. (13), (14), (16), and (17) and the boundary conditions in Eq. (5b) obtains the relationship of the plastic zone width to gas pressure and other factors as follows:

\[ \left( p_i + \frac{c_t}{\tan \phi_c} \left( \frac{1 - H \tan \phi_p}{H} + \frac{1 - H \tan \phi_p L}{10H + \tan \phi_p H L} \right. \right) \]

Substituting the equation used in this paper is consistent with the actual distribution of stress in the plastic activity area and explains the uncertainty of vertical stress distribution in the elastic activity area by using the dashed line connection. Furthermore, the evaluated coal seam instability criterion is the width of the plastic activity area. Therefore, the vertical stress distribution of the elastic activity area will not affect the accuracy of the research results.

According to the parameters provided in Table 1, the M–C, D–P, and Wilson criteria are applied. Consequently, the disturbance and plastic zones widths are obtained and shown in Table 3.

Table 2 shows that the coal seam plastic zone width and the vertical stress peak obtained on the basis of D–P criterion are

<table>
<thead>
<tr>
<th>Strength criterion</th>
<th>Vertical stress ( \sigma_y ) (MPa)</th>
<th>Plastic zone width degree ( x_p ) (m)</th>
<th>Elastic zone width degree ( x_e ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M–C</td>
<td>42.53</td>
<td>8.431</td>
<td>1.206</td>
</tr>
<tr>
<td>Wilson</td>
<td>27.87</td>
<td>8.021</td>
<td>1.616</td>
</tr>
</tbody>
</table>

4. A case study

The roadway width and height of the coal mine are 3 and 3.5 m, respectively. Table 1 provides a list of the physical and mechanical parameters of the coal seam. Substituting these parameters into Eqs. (20) and (21) obtains the stress distribution in the horizontal and vertical directions, as shown in Fig. 4.

The stress distribution obtained by the constitutive equation used in this paper is consistent with that of Lippmann: the vertical stress changes at the junction of the elastic and plastic activity areas [9]. Lippmann also argued that if the outburst is stopped with boundary friction, then the pressure distribution should be discontinuous. Nonetheless, this pressure distribution has never been measured on-site and in the laboratory.

To ensure the accuracy of the present study, a large number of field-related measured data are reviewed. Results showed the gradual decrease in the distribution of vertical stress in the elastic activity area [25]. However, the vertical stress of the constitutive equation used in this paper is consistent with the actual distribution of stress in the plastic activity area and the original rock disturbance area. To ascertain the accuracy and validity of the article, this study evaluates the vertical stress distribution of the elastic activity area and explains the uncertainty of vertical stress distribution in the elastic activity area by using the dashed line connection. Furthermore, the evaluated coal seam instability criterion is the width of the plastic activity area. Therefore, the vertical stress distribution of the elastic activity area will not affect the accuracy of the research results.

According to the parameters provided in Table 1, the M–C, D–P, and Wilson criteria are applied. Consequently, the disturbance and plastic zones widths are obtained and shown in Table 3.

Table 2 Calculation results obtained by applying the mathematic model.

Fig. 4. Distribution of stress in the coal seam.
8.875 m and 46.47 MPa, respectively; the coal seam plastic zone width and the vertical stress peak determined on the basis of M–C criterion are 8.431 m and 42.53 MPa, respectively; and the coal seam plastic zone width and the vertical stress peak found according to the Wilson criterion are 8.021 m and 27.87 MPa, respectively. Evidently, the plastic zone width and the vertical peak stress obtained by using the Wilson material yield criterion are the smallest and most conservative, whereas the results obtained by using the circumcircle D–P criterion are the largest ones. The use of D–P criterion to assess the seam rockburst destabilization is the safest method.

5. Analysis of factors affecting plastic zone width

Many researchers have studied the plastic zone width, which can be used as an index to evaluate the coal seam destabilization and failure. The large plastic zone width and closeness to the disturbance zone width result in easy occurrence of destabilization.

5.1. Effects of multiple parameters on plastic zone width

In order to analyze the effect of influencing parameters on the width of the plastic zone, various parameters in Eq. (21) are

![Diagram](https://example.com/diagram.png)

**Fig. 5.** Relationship of plastic zone width to various parameters.
evaluated based on the D–P criterion, the Refs. [12,13,15] and the actual measurement data. The parameters are divided into three groups as shown in Table 3: roadway width–height, support resistance-coal strength (internal friction angle) and support resistance-underground stress. These three groups parameters are calculated with Eq. (21) to study the effects of these data on the width of the plastic zone and the results are shown in Fig. 5.

According to Fig. 5(a), the width of the plastic zone continuously increases with the increased roadway height and slightly increases with increased roadway width, thereby showing a nearly linear relationship. The roadway height exerts more remarkable effect on the plastic zone width than that of the roadway width. Comparison of the three groups in Fig. 5(a) revealed that with the increased gas pressure, the effects of roadway height–width on the plastic zone width exhibit approximately the same trends, and the plastic zone width consecutively increases.

Fig. 5(b) illustrates that (1) the plastic zone width decreases continuously with the increased internal friction angle and slightly decreases with the increased support resistance, (2) the effect of support resistance on the plastic zone width increases gradually with the decrease in the internal friction angle of the coal, (3) the effect of coal internal friction angle on the plastic zone width increases gradually with the decrease of support resistance, and (4) the coal internal friction angle exerts a more remarkable effect on the plastic zone width than that of the support resistance. Additionally, with the increased gas pressure, the effects of coal internal friction angle-support resistance on the plastic zone width display approximately the same trends.

Fig. 5(c) demonstrates that (1) the plastic zone width increases continuously with the increase in underground stress but decreases continuously with the decrease in support resistance, and (2) the small support resistance results in remarkably evident effect of underground stress on the plastic zone width. In addition, the effects of underground stress-support resistance on the plastic zone width show approximately the same trends. The plastic zone width also constantly increases with the increased gas pressure.

In summary, the plastic zone width can be reduced by optimizing the support ways, improving the coal strength, and changing the roadway size, thereby reducing the risk of coal seam rockburst destabilization.

5.2. Effect of gas pressure on plastic zone width

Gas pressure affects the plastic zone width. To further reflect the effect of gas on coal seam destabilization, this study investigates the effects of different gas pressures on coal seam stress distribution and plastic zone width and analyzes the effect of gas on coal seam destabilization. Table 4 presents a list of the material parameters of gas-bearing coal.

Fig. 6 shows the distribution of calculated stress of coal seam on both sides of roadway under different gas pressure conditions. According to the results given in Table 5, when the other conditions are the same, the gas pressure exerts considerable effect on the plastic zone width and vertical stress, and the plastic zone width and the coal seam stress increase with the increased gas pressure, and the destabilization risk of the coal seam after

### Table 4

<table>
<thead>
<tr>
<th>No.</th>
<th>h (m)</th>
<th>k</th>
<th>p (MPa)</th>
<th>q (MPa)</th>
<th>b (m)</th>
<th>c (MPa)</th>
<th>tan φ (°)</th>
<th>φ (°)</th>
<th>c (MPa)</th>
<th>x</th>
<th>μ</th>
<th>p (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.75</td>
<td>0.8</td>
<td>0.2</td>
<td>17.8</td>
<td>1.5</td>
<td>0.5</td>
<td>0.1</td>
<td>22</td>
<td>3</td>
<td>0.15</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>1.75</td>
<td>0.8</td>
<td>0.2</td>
<td>17.8</td>
<td>1.5</td>
<td>0.5</td>
<td>0.1</td>
<td>22</td>
<td>2</td>
<td>0.15</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>1.75</td>
<td>0.8</td>
<td>0.2</td>
<td>17.8</td>
<td>1.5</td>
<td>0.5</td>
<td>0.1</td>
<td>22</td>
<td>1</td>
<td>0.15</td>
<td>0.3</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Table 5

<table>
<thead>
<tr>
<th>No.</th>
<th>Plastic zone width (m)</th>
<th>Elastic zone width (m)</th>
<th>Vertical stress (MPa)</th>
<th>Horizontal stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.742</td>
<td>3.895</td>
<td>39.7</td>
<td>11.7</td>
</tr>
<tr>
<td>2</td>
<td>7.235</td>
<td>2.402</td>
<td>43.9</td>
<td>12.5</td>
</tr>
<tr>
<td>3</td>
<td>9.357</td>
<td>0.28</td>
<td>47.3</td>
<td>14.1</td>
</tr>
</tbody>
</table>
disturbance increases. When the gas pressure is 3 MPa, the elastic zone width is 0.28 m; the plastic zone width is 9.357 m, which is the most approximate to the disturbance zone width; the stress in the vertical direction is 47.3 MPa; and the stress in the horizontal direction is 14.1 MPa. Consequently, the maximum values are reached.

6. Conclusions

The drawn conclusions are as follows:

1. On the basis of Lippmann rockburst basic theory, this study considers the support resistance, introduces the mathematical model for gas pressure distribution, adopts the unified expression of the Wilson, M–C, and circumcircle D–P criteria in the plane strain state, establishes the model for translation outburst of the full-roadway coal seam with its roof and floor being rocks, and finally applies the distribution of stress on both sides of the roadway. Thus, this study can provide a theoretical basis for the prediction and forecasting of rockburst.

2. Solving the actual production of some coal mining area determines that the plastic zone width obtained by using the Wilson and M–C material yield criteria and the peak stress in the vertical direction are small. Thus, the obtained results are the most conservative results. Moreover, the use of D–P criterion to assess the seam rockburst destabilization is the safest.

3. Studying the effects of multiple parameter models on the plastic and disturbance zone widths reveals that the coal seam stability is related to gas pressure, and high-pressure gas accelerates the coal seam destabilization. The plastic zone width is slightly affected with the roadway width, and it continuously increases with the increased roadway height. The large support resistance and high coal strength result in small plastic zone width. Changing the roadway size and support can reduce the width of the plastic zone, thereby lowering the risks of coal seam destabilization. Therefore, studies on the mechanism of coal seam destabilization should consider the relationship with gas disasters.

Acknowledgments

The authors would like to acknowledge the support of National Natural Science Foundation of China (Nos. 51674158 and 51604168), and the Natural Science Foundation of Shandong Provincial (No. ZR2016EEQ18), and the Source Innovation Program (Applied Research Special-Youth Special) of Qingdao (No. 17-1-1-38-jch), Shandong University of Science and Technology Research Fund (No. 2015JQH105), and the Taishan Scholar Talent Team Support Plan for Advantaged & Unique Discipline Areas.

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Please cite this article in press as: Gang W et al. Strength criterion effect of the translator and destabilization model of gas-bearing coal seam. Int J Min Sci Technol [2018], https://doi.org/10.1016/j.ijmst.2018.04.006