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Rock Burst and Instability Analysis for Coal Roadways Based on Unified Strength Theory

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Abstract: Based on the unified strength theory (UST), a model of rock burst and instability was established in this paper, with which the effects of intermediate principal stress (IPS) and coal seam strength parameters (cohesion and inner friction angle) on the distribution characteristics of vertical stress on coal roadway as well as plastic zone width was discussed. This model is compared with models based on Mohr-Coulomb criterion and Drucker-Prager criterion respectively. Accordingly, the features of the said effects was obtained. The results show that the unified solution in terms of UST is of widespread theoretical significance in that it collects a series of ordered pairs as solutions; in comparison, the solution for rock burst and instability using Mohr-Coulomb criterion is partially conservative, while the Druker-Prager criterion counterpart is too dangerous; the change of IPS and inner friction angle leads to markedly varying evaluation results of rock burst and instability. The key to reasonable assessment on rock burst and instability lies in a full consideration of the effects of IPS and coal seam strength parameters (cohesion and inner friction angle).

Keywords: *coal roadway; rock burst and instability; intermediate principal stress; vertical stress; yield criterion*

1. Introduction

As a complicated coal rock dynamic phenomenon, rock burst always unleash drastic elastic energies powerful enough to destroy underground apparatus, collapse roadways over 100 meter long, or kill people [1-5]. As coal mining extends to greater depths, rock burst behaviors are increasingly intensified, which causes a reasonable number of casualties and financial losses. For example, a fatal accident of 10 dead, 65 injured, and a direct financial loss of 27.4848 million RMB resulted from the rock burst in No. 21221 working face roadway in Qianqiu Coal Mine, Henan province on Nov. 3rd, 2011 [4]. Rock busrt is on their way towards one of the gravest dynamic disasters in Chinese coal mines. Therefore, in light of safety coalmine production, it is of great significance to study on the mechanism of rock burst and instability.

Coal seam bumps and instability is typical of rock burst and instability[6]. Lippmann set up the fundamental theory of coal seam bumps and instability using Mohr-Coulomb criterion, aiming to reveal the mechanism of coal seam bumps and instability[7]; Jiang Yaodong employed Hoek-Brown criterion to establish a mechanical model of coal seam bumps and instability[8]. Jiang Fuxing included the effect of intermediate principal stress in the mine bump and instability model established based on Druker-Prager criterion[9]. However, both Mohr-Coulomb criterion and Hoek-Brown criterion neglect IPS impact, while IPS impact is assimilated with the effect of minimum principal stress in Druker-Prager criterion. With respect to complex coal seam structures and environmental factors[10-12], it is a necessity to obtain unified solutions for rock burst and instability in provision of theoretical basis for rock burst and instability analysis. In recent years, UST has found widespread application to fields of geotechnical engineering and coal mining[13-14]. This theory features a proper reflection of material IPS, explicit physical meanings, segmented linear expression, and ease access to analytical solutions. A new UST system has born of the theory. On its basis, the unified solution for elastic-plastic mechanics in coal burst and instability was established. The evaluation result was compared with those obtained based on Mohr-Coulomb criterion and Drucker-Prager criterion respectively. By using the single factor analysis method, the characteristics of the effects of IPS and coal seam strength parameters (cohesion and inner friction angle) on coal seam burst and instability was discussed, which intends to provide a thought of assessment on rock burst and instability.

2. Unified strength theory

UST takes into full consideration σ2 effect and interval features of IPS, and fits to analyze deformation characteristics of materials of different compressive behaviors. Let compressive stress be positive, and define two basic material parameters (cohesion c and inner friction angle φ). Therefore, the formula of UST under plane stress was expressed as[15-16]

$$\left.\begin{aligned} &\sigma_2 \le \frac{\sigma_1+\sigma_3}{2}-\frac{\sigma_1-\sigma_3}{2}\sin\varphi \\ &F=\frac{1+\sin\varphi}{1-\sin\varphi}\sigma_1-\frac{b\sigma_2+\sigma_3}{1+b}=\frac{2\cos\varphi}{1+\sin\varphi} \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} &\sigma_2 \ge \frac{\sigma_1+\sigma_3}{2}-\frac{\sigma_1-\sigma_3}{2}\sin\varphi \\ &F^{/}=\frac{(1-\sin\varphi)(b\sigma_2+\sigma_1)}{(1+\sin\varphi)(1+b)}-\sigma_3=\frac{2c\cos\varphi}{1+\sin\varphi} \end{aligned}\right\} \quad (2)$$

Where b was the UST parameter that reflected the degree to which intermediate principal shear stress and the positive stress above it contributed to material yield/failure, known as IPS σ_2 effect, $0 \leqq b \leqq 1$.Different b values corresponded to different yield criteria. When $b=0$, UST regressed to Mohr-Coulomb criterion; when $b=1$, UST changed into double shear yield criterion; and when $0<b<1$, UST presented itself as a series of new yield criteria.

Coal seam was conceptualized as evenly-distributed, continuous, isotropic and ideal elastic-plastic material, as shown in Figure 1. The roadway was under plane stress. Its vertical stress σ_z was IPS, and $\sigma_z=\sigma_2=(\sigma_1+\sigma_3)/2$[17], such that satisfying Equation (2).

The final formula of UST under plane stress was

$$\left.\begin{aligned} &\sigma_1=\frac{1+\sin\varphi_t}{1-\sin\varphi_t}\sigma_3+\frac{2c_t\cos\varphi_t}{1-\sin\varphi_t} \\ &\sin\varphi_t=\frac{2(1+b)\sin\varphi}{2+b(1+\sin\varphi)} \\ &c_t=\frac{2c(1+b)\cos\varphi}{2+b(1+\sin\varphi)}\frac{1}{\cos\varphi_t} \end{aligned}\right\} \quad (3)$$

Where c_t, φ_t were unified cohesion and unified internal friction angle respectively.

3. UST-based analysis of coal burst and instability

3.1 Mechanical of coal burst and instability

Rock burst and instability happens when coal rock bursts out under the action of strong stress or dynamic disturbance. Research findings show that high-degree stress concentration formed during coal exploitation is the main cause to rock burst and instability. High-degree stress concentration in roadways at great depth is always in the form of concentrated vertical stress exerted on roadways. The value of this vertical stress and plastic zone width are crucial indicators of perilous behaviors of coal outburst in roadways [1,18]. Higher peak value of vertical stress and narrower plastic zone correspond to more dangerous behaviors; lower peak value of vertical stress and wider plastic zone reduce outburst intensity. Stress on roadway wall rock is redistributed as a response to coal excavation, which always lead to the rise in vertical stress on roadways before the phenomenon of stress concentration appears. As coal excavation continues on, there is a moment when the vertical stress exceeds the threshold for coal burst and instability, and coal bumps occur accordingly.

3.2 Fundamental assumptions and mechanical model

The research issue was converted into the problem of plane stress, and several necessary assumptions was proposed: (1) the coal seam is evenly-distributed, continuous, isotropic, and ideally elastic-plastic; (2) the dip angle is zero; the roadway layout is horizontal; and the roadway length can extend infinitely; (3) the coal seam is under and only under the action of overburden gravity, irrespective of dead weight; (4) the roof is parallel with coal seam floor; the roof, the floor and the coal seam itself share the same sliding resistance; (5) the sliding friction along coal seam interfaces satisfies Coulomb criterion.

Figure 1 is the mechanical model of coal roadway. The undisturbed coal seam as thick as $2h$ is under the action of vertical stress q and horizontal stress λq. Here are some related parameters: roadway height $2h$, roadway width $2a$, plastic zone length x_p, disturbed zone length L, roadway support resistance p_0, vertical stress on roadway coal seams during roadway work σ_y. In the following content, the superscripts “e”、“p” was used to represent “within the elastic zone” and “within the plastic zone” respectively.

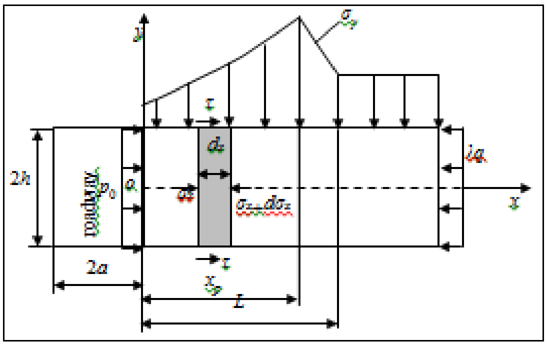

Figure 1. *Mechanical model of coal roadway*

3.3 Vertical stress on coal seams in the plastic zone

As can be seen from Figure 1, a micro unit at the height of $2h$ was cut out of roadway coal rock, and then bear a horizontal force and a pair of friction resistances on its top and bottom. It’s assumed that the shear stress was evenly distributed, and that the shear failure plane was parallel with coal seam interface. According to equilibrium condition, a differential equation of equilibrium along the horizontal direction was established as equation (4).

$$\tau=h\frac{d\sigma_x}{dx} \quad (4)$$

With the aid of Coulomb criterion, the shear stress on coal seam interface could be expressed as equation (5).

$$\tau = c_0 + \sigma_y \tan\varphi_0 \tag{5}$$

Where c_0, φ_0 denoted interface cohesion and interface friction angle respectively.

Within the plastic zone for roadway wall rock, $\sigma_y=\sigma_1, \sigma_x=\sigma_3$. Through equations (3)-(5), and by using the equilibrium condition that when $x=0, \sigma_x=p_0$. Accordingly, the vertical stress on coal seam within the plastic zone was expressed as

$$\sigma_y^p = \left(c_0 \cot\varphi_0 + \frac{(1+\sin\varphi_t)p_0 + 2c_t \cos\varphi_t}{1-\sin\varphi_t} \right) \times \exp\left(\frac{(1+\sin\varphi_t)\tan\varphi_0}{(1-\sin\varphi_t)h} x \right) - c_0 \cot\varphi_0 \tag{6}$$

3.4 Vertical stress on coal seams in the elastic zone

In the elastic zone, there was

$$\frac{\sigma_y^e}{\sigma_x^e} = \frac{1-\mu}{\mu} \tag{7}$$

Through equations (4) (5) (7), and by using the condition that when $x=L, \sigma_x=\lambda q$. Accordingly, the vertical stress on coal seam within the elastic zone was expressed as

$$\sigma_y^e = (q + c_0 \cot\varphi_0) \exp\left(\frac{1-\mu}{\mu \cot\varphi_0} \frac{L-x}{h} \right) - c_0 \cot\varphi_0 \tag{8}$$

3.5 Plastic zone length and disturbance zone length

Through equations (6) and (8), and by using the advantage of the continuity of vertical stress on coal seams at the point where $x=x_p$. Thus, the plastic zone length was obtained as

$$x_p = h \cot\varphi_0 [\frac{1-\mu}{\mu} \frac{\tan\varphi_0}{h} L - \ln \frac{c_0 \cot\varphi_0 + \frac{(1+\sin\varphi_t)p_0 + 2c_t\cos\varphi_t}{1-\sin\varphi_t}}{q + c_0 \cot\varphi_0}] / (\frac{1-\mu}{\mu} + \frac{1+\sin\varphi_t}{1-\sin\varphi_t}) \tag{9}$$

During excavation, the load on roadway was bear by neighboring coal seams. Based on stress equilibrium before and after excavation, there was

$$aq = \int_0^{x_p} \sigma_y^e \mathrm{d}x + \int_{x_p}^{L} \sigma_y^p \mathrm{d}x \tag{10}$$

Through equations (6) (8) (10), and took advantage of the boundary condition $x=0, \sigma_x=p_0; x=L, \sigma_x=\lambda q$. Thus, the disturbance zone length can be expressed as equation (11).

$$L = \frac{(\lambda - \frac{p_0}{q} - \frac{a}{h}\tan\varphi_0)h}{\frac{c_0}{q} + \tan\varphi_0} \tag{11}$$

4. Cases and parameter analysis

In order to discuss the effects of IPS, cohesion and internal friction angle on coal burst and instability evaluation, some data samples in document was referred [8,9], including roadway width of 4m, roadway height of 4.8m, 20MPa vertical stress on coal seams, pressure coefficient λ of 0.8, Poisson's ratio μ of 0.3, coal seam cohesion c of 1.66MPa, coal seam internal friction angle φ of 18.6°, coal seam interface cohesion c_0 of 0.8MPa, coal seam interface friction angle φ_0 of 5.8°, support resistance p_0 of 0.4MPa.

4.1 IPS effect

Figure 2 is vertical stress on coal seam under different intermediate principal stresses. According to this figure, the curve agrees well with typical characteristics of vertical stress distribution on coal seams; when coal seam parameters remain unchanged, the disturbance zone width is fixed as such unaffected by yield criterion; under the unified strength yield criterion, as b value increases, the plastic zone of coal seams becomes shorter, and the vertical stress on coal seams inclines gradually.

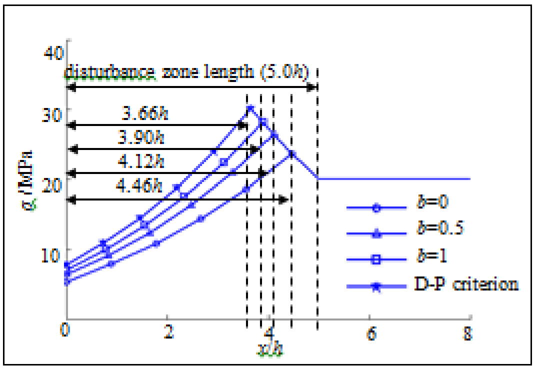

Fig.2 *Yertical stress on coal seam under different intermediate principal stresses*

Figure 2 shows that when b=0, Mohr-Coulomb criterion dominates, which means no IPS effect in coal seams. The plastic zone length is 4.46h, and the peak value of vertical stress is 23.67MPa; when b=1, the curve corresponds to double shear yield criterion, which means the maximum IPS effect in coal seams. The plastic zone length is 3.90*h*,and the peak value of vertical stress is 28.06MPa. Under Druker-Prager criterion, the plastic zone length is 3.66*h*, and the peak value of vertical stress is 30 MPa. Therefore, by contrast, the longer plastic zone and lower peak value of vertical stress obtained under Mohr-Coulomb criterion can easily lead to an underestimation of the risk of rock burst and instability. While the shorter plastic zone and higher peak value of vertical stress obtained under Druker-Prager criterion tend to cause an overestimation of the risk of rock burst and instability.

4.2 Efect of internal friction angle *φ*

The internal friction angle *φ* commonly ranges from 16° to 40°[19]. Figure 3 is relation curves between internal friction angle and vertical stress peak, and Figure 4 is relation curves between internal friction angle and plastic zone width. As can be seen from them, the increase of *φ* is accompanied by the nonlinear rise in vertical stress peak under UST-based and D-P criterion, while the plastic zone width x_p presents nonlinear decrease at the same time. When *b*=0.5,the vertical stress peak at *φ*=40°increases by 67.8% in comparison to the one at *φ*=16°, while the plastic zone width decreases by 42.4%. This result indicates that coal seam internal friction angle exerts significant influence on vertical stress peaks and plastic zone widths in roadways. Importance should be attached to coal seam internal friction angle during evaluation on coal bumps and instability.

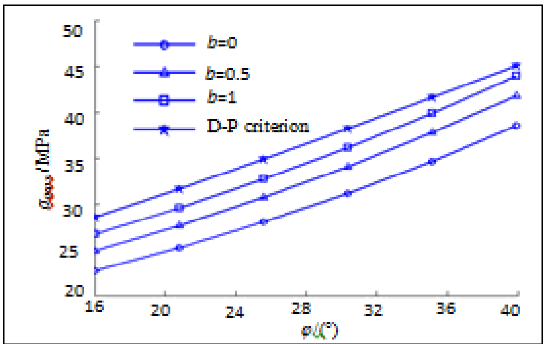

Fig.3 *Relation curves between internal friction angle and vertical stress peak*

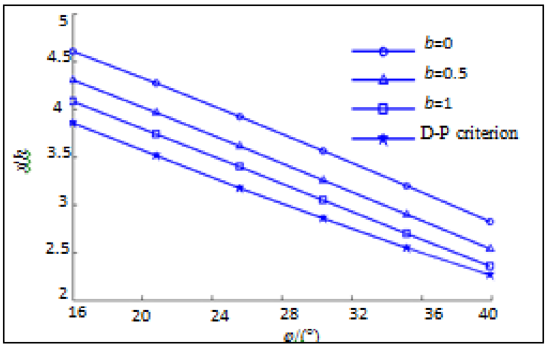

Fig.4 *Relation curves between internal friction angle and plastic zone width*

4.3 Effects of cohesion *c*

The coal seam cohesion c commonly falls into the interval of 1.0~9.0MPa[19]. Figure 5 is relation curves between internal cohesive force and plastic zone width, and Figure 6 is relation curves between internal cohesive force and vertical stress peak. As can be seen from them, the increase of cohesion is accompanied by the nonlinear rise in vertical stress peak under UST-based and D-P criterion, while the plastic zone width x_p presents nonlinear decrease at the same time. When *b*=0.5, the vertical stress peak when *c*=9 increases by 112% in comparison to the one when *c*=1, while the plastic zone width decreases by 84.9%. This result indicates that coal seam internal cohesion exerts significant influence on evaluation on coal burst and instability.

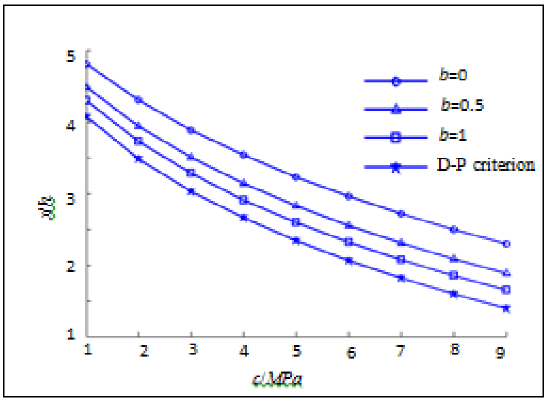

Fig.5 *Relation curves between internal cohesive force and plastic zone width*

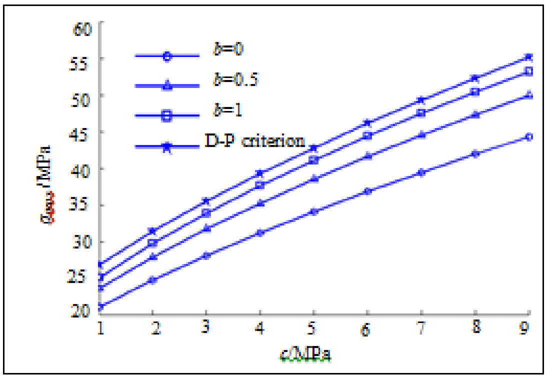

Fig.6 *Relation curves between internal cohesive force and vertical stress peak*

5. Conclusion

(1) The UST-based distribution of vertical stress and plastic zone distribution is a series of ordered pairs. When *b*=0, UST regresses to Mohr-Coulomb criterion; when *b*=1, UST changes into double shear yield criterion. Multiple parameter selection is also allowed in the unified strength theory. Therefore, this theory is of wide theoretical meanings.

(2) The selection of yield criterion greatly influence the distribution characteristics of vertical stress on coal seam in roadways and plastic zone. Under the same condition, the longer plastic zone and lower peak value of vertical stress obtained under Mohr-Coulomb criterion can easily lead to an underestimation of the risk of rock burst and instability. While the shorter plastic zone and higher peak value of vertical stress obtained under Druker-Prager criterion tend to cause an

overestimation of the risk of rock burst and instability.

(3) The UST parameter *b*, coal seam strength parameters *c*, and *φ* influence the evaluation result of rock burst and instability remarkably. As *b*, *c*, and *φ* increase, the vertical stress increases, while the plastic zone length decreases gradually. Given this, the key to evaluation on rock burst and instability lies in a reasonable consideration of intermediate principal stress and coal seam strength parameters.

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