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Elastic-plastic comparison and analysis on surrounding rock of gas drainage borehole based on M-C criterion and D-P criterion

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ABSTRACT

Gas drainage is one most important technical measure of controlling gas for high gassy coal mines, and the state of stress-strain is closely related to the stability of surrounding rock of borehole. The Yield criterion is the principal condition for judging the plastic of surrounding rock. M-C criterion and D-P criterion, which are widely used in numerical simulation, are basically related with the influences such as cohesive force, internal friction angle, in-situ stress and so on. However, these criterions have different functions and yield surface, especially without considering the mid-principal stress effect for Mohr-Coulomb yield criterion. Thus, elastic-plastic analysis of surrounding rock on gas drainage borehole under various yield criterions are proposed for comparing the effect of different mechanic characteristics of surrounding rock on the stress and displacement of elastic-plastic zones and the radius of plastic zone. And the results are preferably used for choosing a suitable yield criterion for the model calculations according to the different surrounding rock characteristics, in order to ensure the security of gas drainage engineering practice even better.

Key words: Circular borehole; Yield criterion; Elastic-plastic analysis; Gas drainage

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INTRODUCTION

Yield criterion is the necessary obeyed condition for describing one point of shaped mass in different stress states changed into plastic state and inducing the plastic deformation to continue [1], which is the key condition for judging the stability of rock. The analysis on the elastic and plastic of surrounding rock around roadway is one of the basic problems in the stability research of rock-soil engineering [2]. As to the high methane mines, the drainage borehole can be regarded as one special example of the axial symmetry circular roadway. And the instable damage maybe induce the invalid of boreholes, which maybe bring a large amount negative impact on the effect of gas drainage. In the process of judging the rock stability, the simulation calculation is one common technical method, including more advantages such that it is easy to realize and reduces the cost with good repetitiveness. So the common simulation software for analyzing rock mechanics such as Ansys, FLAC and Comsol, are widely liked by the major engineers. And their mechanics modulus all includes M-C criterion and D-P criterion [3], [4], [5]. Although M-C criterion and D-P criterion have differences in function and yield face, they are both related with cohesive force, internal friction angle, in-situ stress and so on. The instable damage of borehole is intently related with the stress distribution rule. And with the change in the driving depth of borehole in seam, the surrounding coal mass can be divided into the stress decline zone, the post-peak stress increase zone, the pre-peak stress increase zone and the original stress zone. While the coal and rock mass in the stress decline zone is usually plastic, and reduces a lot of fractures, the instable damage even the caving maybe occur due to the tiny turbulence. As a result, the borehole cannot play a positive role in drainage [6]. The stress distribution of surrounding rock around borehole is closely related to the characteristics parameters of surrounding rock. So the analysis on the effect on the stability of drainage boreholes of cohesive force, internal friction angle, in-situ stress, elastic modulus, passion's ratio and so on, can provide the theoretical basis for the stability pre-judge of borehole before the excavation in various coal-rock types.

1.Yield criterion analysis

In 1900, Mohr established the M-C criterion to describe the strength characteristics of rock or soil. The yield face of this criterion in three dimension space is the irregular pyramid surface of hexagonal cross section, and the yield curve in π plane is hexagon with unequal angles. Even there are cusp and edges. In addition, it neglects the action of middle principal stress [7]. And the function of M-C criterion is

$$f = (\sigma_1 - \sigma_3)/2 - \sin\varphi(\sigma_1 + \sigma_3)/2 - c\cos\varphi = 0 \qquad (1)$$

In 1952, Drucker and Prager enlarged Mises criterion to the wide Mises criterion in considering the effect of hydrostatic pressure. And the yield face in principal space is a cone surface with the shaft of isoclinic line. The yield curve inπ plane is circular. And this criterion considers the action of middle principal stress, which is opposite to M-C criterion [8]. The function of this criterion is

$$f(I_1, \sqrt{J_2}) = \sqrt{J_2} - \alpha I_1 - k = 0 \qquad (2)$$

where, α and $k$are the parameters related with cohesive force and internal friction angle. Drucker and Prager enduced Drucker-Prager criterion, which is in accordance with M-C criterion in the state of plane strain under the associated flow rule. This criterion is also named as M-C inscribed circle rule DP3. And the functions of α and$k$are,

$$\alpha = \sin\varphi / \sqrt{9 + 3\sin^2\varphi}$$
$$k = 2c\cos\varphi / \sqrt{9 + 3\sin^2\varphi} \qquad (3)$$

where,I_1 is the first invariable amount of stress tensor, and J_2 is the second invariable amount of stress deviator, with the functions of

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3$$
$$J_2 = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]/6 \qquad (4)$$

In this thesis, the middle principal stress coefficient b is introduced to express the relation among the middle principal stress, the maximum and minimum principal stress [9], [10]. (The compression stress is positive, $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$). And the expression of b is

b=(σ2-σ3)/(σ1-σ3)(5)

Combine the equations (2), (4) and (5), then obtain

$$(m - \alpha - b\alpha)\sigma_1 - (m + 2\alpha - b\alpha)\sigma_3 - k = 0 \qquad (6)$$

where $m = \sqrt{(b^2 - b + 1)/3}$. And Eq.(6) can be regarded as another expression of D-P criterion.

2. Elastic-plastic analysis of surrounding rock around drainage borehole

2.1 Basic assumptions

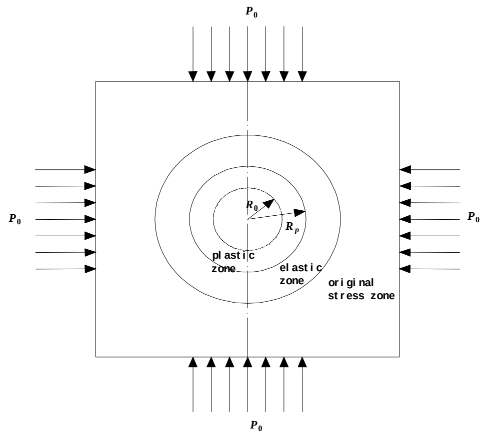
I. The gas drainage is the horizontal circular one in deep. So in order to calculate easily, the borehole is assumed as infinite long and the strain state is plane strain one.

II. The original stress is equal for every direction, with the amount of P0, shown in Fig.1.

III. The surrounding rock is continuous, homogeneous, isotropic elastic-plastic body, when the rock reaches the yield limit it damages.

IV. Choose anaffirmative element from the surrounding rock of the borehole.Assume radial stressσr, tangential stressσθand axial stress σz stand by the element orthogonal with each other, as shown in Figure 2. There may be $\sigma_\theta \geq \sigma_z \geq \sigma_r$, $\sigma_\theta = \sigma_1$, $\sigma_z = \sigma_2$, $\sigma_r = \sigma_3$. To be clear,σre,σθe,σrp, σθp are respectively radial stress and tangential stress of elastic zone and radial stress and tangential stress of plastic zone.

V. The volume of surrounding rock around borehole is constant.



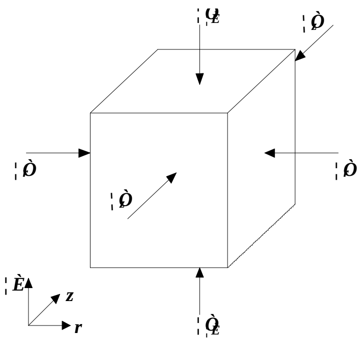


Fig.1 Mechanics model of gas drainage borehole **Fig.2 Mechanics model of micro element in surrounding rock in Polar coordinate**

2.2 Basic equations

Elastic zone:

According to the basic theory of elastic mechanics [11], the elastic stress solution with uncertain integral constant coefficient is

$$\sigma_{re} = A + \frac{B}{r^2}, \sigma_{\theta e} = A - \frac{B}{r^2} \quad (7)$$

Plastic zone:

For axisymmetric plane strain problem, the balance equation is

$$\frac{d\sigma_{rp}}{dr} + \frac{\sigma_{rp} - \sigma_{\theta p}}{r} = 0 \quad (8)$$

By assumption IV, strength criterion expression can be converted to:

I. M-C criterion

$$\sigma_{\theta p} = \frac{1+\sin\theta}{1-\sin\theta}\sigma_{rp} + \frac{2c\cos\theta}{1-\sin\theta} \quad (9)$$

II.D-P criterion

$$(m - \alpha - b\alpha)\sigma_{\theta p} - (m + 2\alpha - b\alpha)\sigma_{rp} - k = 0 \quad (10)$$

Boundary conditions:

The inner boundary of plastic zone is the borehole wall, and $r = R_0$, $\sigma_r = 0$;

The outer boundary of plastic zone is elastic-plastic interface in the surrounding rock of the borehole, and $r = R_p$, $\sigma_{rp} = \sigma_{re}$, $\sigma_{\theta p} = \sigma_{\theta e}$;

The inner boundary of elastic zone is the outer boundary of plastic zone, and $r = R_p$,

$\sigma_{re} = A + \frac{B}{R_p^2}$, $\sigma_{\theta e} = A - \frac{B}{R_p^2}$;

The outer boundary conditions of elastic zone existthe following relation functions as $r \to \infty$, $\sigma_r = \sigma_\theta = P_0$.

2.3 Elastic-plastic solution analysis on the surrounding rock of borehole

2.3.1 Elastic-plastic Solution based on M-C criterion

Substitute Eq.(9) into Eq.(8) and use the inner boundary condition of plastic zone，

$$\sigma_{rp} = c\cot\varphi[(\frac{r}{R_0})^{\frac{2\sin\varphi}{1-\sin\varphi}} - 1] \quad (11)$$

Substitute Eq.(1) into Eq.(9), there is

$$\sigma_{\theta p} = c\cot\varphi[\frac{1+\sin\varphi}{1-\sin\varphi}(\frac{r}{R_0})^{\frac{2\sin\varphi}{1-\sin\varphi}} - 1] \qquad (12)$$

Use the outer boundary condition of elastic zone, there is A=P0. According to Eq.(7), obtain the following expressions,

$$\sigma_{re}\Big|_{r=R_p} = P_0 + \frac{B}{R_p^2}, \sigma_{\theta e}\Big|_{r=R_p} = P_0 - \frac{B}{R_p^2} \qquad (13)$$

Combine Eq.(11) and Eq.(12), then utilize the outer boundary condition of plastic zone, and get the radius of plastic zone as

$$R_p = R_0[\frac{(1-\sin\varphi)(P_0 + c\cot\varphi)}{c\cot\varphi}]^{\frac{1-\sin\varphi}{2\sin\varphi}} \qquad (14)$$

Combine Eq.(13) and Eq.(14), and utilize the outer boundary condition of plastic zone, then get the expression of B. Substitute B into Eq.(13), there are

$$\sigma_{re} = P_0(1-\frac{R_p^2}{r^2}) + c\cot\varphi\frac{R_p^2}{r^2}[(\frac{R_p}{R_0})^{\frac{2\sin\varphi}{1-\sin\varphi}} - 1] \qquad (15)$$

$$\sigma_{\theta e} = P_0(1+\frac{R_p^2}{r^2}) - c\cot\varphi\frac{R_p^2}{r^2}[(\frac{R_p}{R_0})^{\frac{2\sin\varphi}{1-\sin\varphi}} - 1] \qquad (16)$$

Substitute Eq.(14) into Eq.(15) and (16), then get radial stress and tangential stress of the elastic zone respectively,

$$\sigma_{re} = P_0 - (c\cos\varphi + P_0\sin\varphi)[\frac{(1-\sin\varphi)(P_0 + c\cot\varphi)}{c\cot\varphi}]^{\frac{1-\sin\varphi}{\sin\varphi}}(\frac{R_0}{r})^2 \qquad (17)$$

$$\sigma_{\theta e} = P_0 + (c\cos\varphi + P_0\sin\varphi)[\frac{(1-\sin\varphi)(P_0 + c\cot\varphi)}{c\cot\varphi}]^{\frac{1-\sin\varphi}{\sin\varphi}}(\frac{R_0}{r})^2 \qquad (18)$$

According to constitutive equation and the geometric equation of the plane strain problem in elasticity [6], there are

$$\varepsilon_{re} = \frac{du_e}{dr} = \frac{1-\nu^2}{E}(\Delta\sigma_{re} - \frac{\nu}{1-\nu}\Delta\sigma_{\theta e}) \qquad (19)$$

$$\varepsilon_{\theta e} = \frac{u_e}{r} = \frac{1-\nu^2}{E}(\Delta\sigma_{\theta e} - \frac{\nu}{1-\nu}\Delta\sigma_{re}) \qquad (20)$$

where $\Delta\sigma_{re} = \sigma_{re} - P_0, \Delta\sigma_{\theta e} = \sigma_{\theta e} - P_0$.

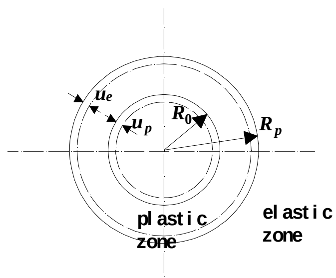


Fig.3 Schematic diagram of elastic-plastic displacement for surrounding rock of the borehole

Handle the deformation of elastic zoneas thick wall cylinder,while the outer boundary is infinite, and the inner boundary radius ofRp. There is support pressure σ_{R_p} in the inner boundary of elastic zone for the plastic zone rock supporting to the elastic zone rock, which can be obtained according to Eq. (15). Assume $r = R_p$, the amount of σ_{R_p} is equal to the radial stress in elastic-plastic junction of surrounding rock. In the outer boundary of elastic zone there is original rock stress of P0. According to Eq.(17)~(20), there exists the following displacement expression in the inner boundary of the elastic zone,

$$u_e\Big|_{r=R_p}=\frac{1+\nu}{E}(P_0-\sigma_{R_p})R_p \quad (21)$$

where, ν is Possion's ration, and E is the elastic modulus of rock mass.
According to Eq.(11) and (15), combine the outer boundary condition of plastic zone, and obtain

$$\sigma_{R_p}=(1-\sin\varphi)P_0-c\cos\varphi \quad (22)$$

Substitute Eq.(22) into Eq.(21), then obtain

$$u_e\Big|_{r=R_p}=\frac{R_p}{2G}\sin\varphi(P_0+c\cot\varphi) \quad (23)$$

where $G=E/2(1+\nu)$.

According to the assumption V, there is the expression as, shown in Fig.3, and up is the plastic displacement and ue is the elastic displacement,

$$[R_p^2-(R_p-u_e)^2]=[R_0^2-(R_0-u_p)^2] \quad (24)$$

Enlarge Eq. (24) and neglect the high order quantities, then obtain

$$u_p=u_eR_p/R_0 \quad (25)$$

Substitute Eq.(14), (21) into Eq.(25), and get the radial displacement of inner wall of borehole as

$$u_p=\frac{R_0\sin\varphi(P_0+c\cot\varphi)}{2G}[\frac{(1-\sin\varphi)(P_0+c\cot\varphi)}{c\cot\varphi}]^{\frac{1-\sin\varphi}{\sin\varphi}} \quad (26)$$

2.3.2 Elastic-plastic Solution based on D-P criterion

Firstly, assume $C=\frac{m+2\alpha-b\alpha}{m-\alpha-b\alpha}$ and $D=\frac{k}{m-\alpha-b\alpha}$, then Eq.(10) can be transformed as

$$\sigma_{\theta p}=C\sigma_{rp}+D \quad (27)$$

Substitute Eq.(27) into Eq.(8), and combine the inner boundary condition of plastic zone,

$$\sigma_{rp}=\frac{D}{1-C}[1-(\frac{r}{R_0})^{C-1}] \quad (28)$$

Substitute Eq.(28) into Eq.(27), and obtain

$$\sigma_{\theta p}=\frac{D}{1-C}[1-C(\frac{r}{R_0})^{C-1}] \quad (29)$$

Use Eq.(5) ,(28) and (29) together with basic assumption IV, then

$$\sigma_{zp}=\frac{D}{1-C}-\frac{D(bC-b+1)}{1-C}(\frac{r}{R_0})^{C-1} \quad (30)$$

Substitute the expressions of C and D into Eq.(27) ~ (30), and obtain the stress solutions of plastic zone,

$$\sigma_{rp}=\frac{k}{3\alpha}[(\frac{r}{R_0})^{\frac{3\alpha}{m-\alpha-b\alpha}}-1] \quad (31)$$

$$\sigma_{\theta p}=\frac{k}{3\alpha}[\frac{m+2\alpha-b\alpha}{m-\alpha-b\alpha}(\frac{r}{R_0})^{\frac{3\alpha}{m-\alpha-b\alpha}}-1] \quad (32)$$

$$\sigma_{zp}=\frac{k}{3\alpha}[\frac{m-\alpha+2b\alpha}{m-\alpha-b\alpha}(\frac{r}{R_0})^{\frac{3\alpha}{m-\alpha-b\alpha}}-1] \quad (33)$$

According to Eq.(13), there exists the relation function of $\sigma_{re}+\sigma_{\theta e}=2P_0$ in the inner boundary of elastic zone. Based on the outer boundary condition of plastic zone, when $r=R_p$, there are $\sigma_{rp}=\sigma_{re}$ and $\sigma_{\theta p}=\sigma_{\theta e}$. Thus, $\sigma_{rp}\big|_{r=R_p}+\sigma_{\theta p}\big|_{r=R_p}=2P_0$, that is

$$\frac{k}{3\alpha}[(\frac{R_p}{R_0})^{\frac{3\alpha}{m-\alpha-b\alpha}}-1]+\frac{k}{3\alpha}[\frac{m+2\alpha-b\alpha}{m-\alpha-b\alpha}(\frac{R_p}{R_0})^{\frac{3\alpha}{m-\alpha-b\alpha}}-1]=2P_0 \quad (34)$$

Simplify and obtain the available expressions for the radius of plastic zone as

$$R_p=R_0[2(\frac{3\alpha P_0}{k}+1)\frac{m-\alpha-b\alpha}{2m+\alpha-2b\alpha}]^{\frac{m-\alpha-b\alpha}{3\alpha}} \quad (35)$$

Substitute Eq.(35) into Eq.(31), and obtain the radial stress in the elastic-plastic junction of surrounding rock around borehole, which is equal to support pressure σ_{R_p} as

$$\sigma_{rp}\big|_{r=R_p}=2(P_0+\frac{k}{3\alpha})\frac{m-\alpha-b\alpha}{2m+\alpha-2b\alpha}-\frac{k}{3\alpha} \quad (36)$$

Substitute Eq. (35) into Eq.(33), and obtain the tangential stress in the elastic-plastic junction of surrounding rock around borehole as

$$\sigma_{\theta p}\big|_{r=R_p}=\frac{k}{3\alpha}[2(\frac{3\alpha P_0}{k}+1)\frac{m-\alpha+2b\alpha}{2m+\alpha-2b\alpha}-1] \quad (37)$$

And the displacement of elastic-plastic zone obeys the relations under D-P criterion as

$$u_p=u_eR_p/R_0 \quad (38)$$

Where, the displacement ue of elastic zone can be obtained from Eq.(13) and (20), expressed as

$$u_e=\frac{(P_0-\sigma_{R_p})R_p}{2GR_0} \quad (39)$$

Substitute Eq.(35) , (36), (39) into Eq.(38), then obtain the expression of the displacement for the inner wall of borehole, which is the radial displacement of plastic zone as,

$$u_p=\frac{R_0(3\alpha P_0+k)}{2G(2m+\alpha-2b\alpha)}[2(\frac{3\alpha P_0}{k}+1)\frac{m-\alpha-b\alpha}{2m+\alpha-2b\alpha}]^{\frac{2(m-\alpha-b\alpha)}{3\alpha}} \quad (40)$$

According to the outer boundary condition of plastic zone, and Eq.(13), (16), then obtain the expression of B under the D-P criterion as,

$$B=\frac{3\alpha P_0+k}{2m+\alpha-2b\alpha}R_p^2 \quad (41)$$

Substitute Eq.(35) and (41) into Eq.(7), then obtain the expressions of radial stress and tangential stress of elastic zone as

$$\sigma_{re}=P_0-\frac{3\alpha P_0+k}{2m+\alpha-2b\alpha}\left(\frac{R_0}{r}\right)^2[2(\frac{3\alpha P_0}{k}+1)\frac{m-\alpha-b\alpha}{2m+\alpha-2b\alpha}]^{\frac{2(m-\alpha-b\alpha)}{3\alpha}} \quad (42)$$

$$\sigma_{\theta e}=P_0+\frac{3\alpha P_0+k}{2m+\alpha-2b\alpha}\left(\frac{R_0}{r}\right)^2[2(\frac{3\alpha P_0}{k}+1)\frac{m-\alpha-b\alpha}{2m+\alpha-2b\alpha}]^{\frac{2(m-\alpha-b\alpha)}{3\alpha}} \quad (43)$$

According the assumption IV, substitute Eq. (42), (43) into Eq. (5) , then obtain the axial stress of elastic zone as

$$\sigma_{ze}=P_0+\frac{(3\alpha P_0+k)(2b-1)}{2m+\alpha-2b\alpha}\left(\frac{R_0}{r}\right)^2[2(\frac{3\alpha P_0}{k}+1)\frac{m-\alpha-b\alpha}{2m+\alpha-2b\alpha}]^{\frac{2(m-\alpha-b\alpha)}{3\alpha}} \quad (44)$$

EXAMPLE ANALYSIS

There is a circular borehole located along the horizontal direction, with the radius R0 of 0.042m, original stress P0 of 15MPa, internal friction angleφ for the surrounding coal mass of 30 degree, cohesive force c of 3MPa, shear modulus G of 1346MPa and volume modulus K of 2917MPa.

3.1 Analysis of the intermediate principal stress effect

Firstly, analyze the intermediate principal stress effect for D-P criterion, calculate and obtain the relative radiusof plastic zone and borehole wall displacement with different intermediate principal stress coefficient, respectively shown in Fig.4 and Fig.5.Where, define the relative radiusof plastic zone as Rp/R0. As shown in Fig.4, the relative radiusof plastic zone reduces firstly and then increases, along with the increases in intermediate principal stress coefficient b. While b is equal to 0, the relative radius of plastic zone reaches the maximum of 2.61. While b is equal to 0.65, the relative radius of plastic zone reaches the minimum of 1.69. But when b is equal to 0.75, the relative radius of plastic zone reaches the minimum of 1.7, which is not so different from the one when b is equal to 0.65. In Figure 5 the results shows that, the wall displacement of borehole also varies as decreased first and then increasedwith the increase of b. When b is equal to 0, the displacement of borehole wall reaches up to the maximum, and the deformation of borehole is also the largest, so the possibility of instability and failure for borehole wall is also larger. While b is equal to 0.75, the displacement of borehole wall reaches down to the minimum. In addition, it can be found from the change law of borehole wall displacement that the range of plastic zone for borehole decreases firstly and then increases, as the intervention of intermediate principal stress. So the ability of surrounding rock around borehole for resisting the failure firstly increases and then decreases. And the figure 4 and 5 clearly reflect the changes of intermediate principal stress on the surrounding rock of the borehole and the instability possibility of borehole. Moreover, both the relative radius of plastic zone and the displacement of borehole wall reach the minimum basically, when b is equal to 0.75. In order to analyze the differences of M-C solution and D-P solution, the following analysis is established based on b=0.75.

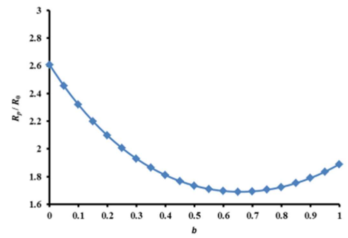


Fig.4 Relation between intermediate principal stress and relative radius of plastic radius

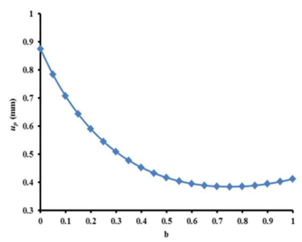


Fig.5 Relation between intermediate principal stress and displacement of borehole wall

3.2 Comparison for the stress in the solutions of M-C criterion and D-P criterion

Calculate and obtain the distribution of stress in the elastic-plastic zones of surrounding rock around borehole under M-C criterion, shown in Fig.6. At a distance of 0.0585m away from borehole wall, the tangential stress reaches to the peak, and it happens to be the rock elastic-plastic junction zone. In addition, the distribution of stress in the elastic-plastic zones of surrounding rock around borehole under D-P criterion while b is equal to 0.75 is shown in Fig.7. At a distance of 0.071m away from borehole wall, the tangential stress reaches to the peak. So there are so many differences in the tangential stress peak in these two criterions. But the radius of plastic zone for D-P criterion is about 1.21 times larger than the one of M-C criterion. Considering the action effect of intermediate principal stress, the range of plastic zone for coal and rock mass increases, and the possibility of instability and damage for coal and rock mass also raise.

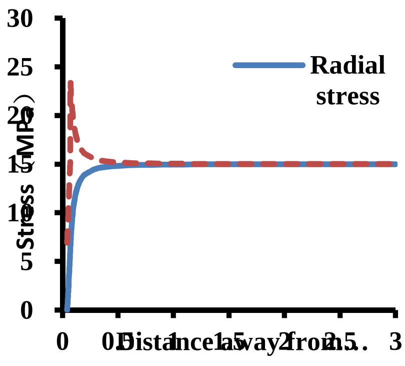


Fig.6 Stress analysis on the stress of elastic-plastic zone for surrounding rock around borehole under M-C criterion

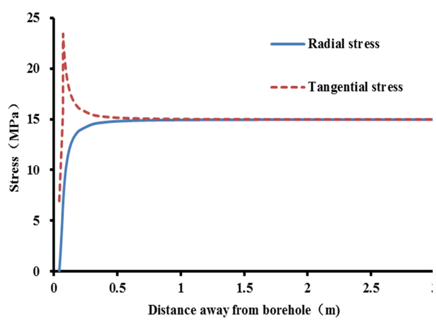


Fig.7 Stress analysis on the stress of elastic-plastic zone for surrounding rock around borehole underD-P criterion

3.3 Influence analysis of characteristics parameters of surrounding rock on the calculation results

3.3.1 Influence analysis of cohesive force

While the change interval of cohesive force is 1~10MPa, internal friction angle is 30degree, original stress is 15MPa and the intermediate principal stress coefficient is 0.75, the influence of different cohesion on hole wall displacement and relative plastic zone radius is shown as figure 8, 9. For these two kinds of criteria, relative radius of plastic zone and borehole wall displacement decrease with the increase of cohesion gradually. It is worth noting, that when cohesive is less than or equal to 7MPa, the calculation results for these two kinds of criterionshavea big difference. And with the increase in cohesion, the difference turns the decreasing trend.

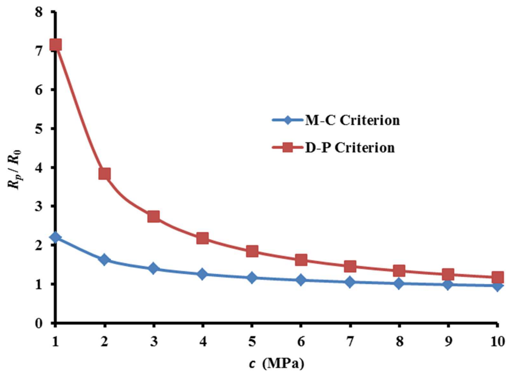


Fig.8 Influence of cohesion on relative radius of plastic zone

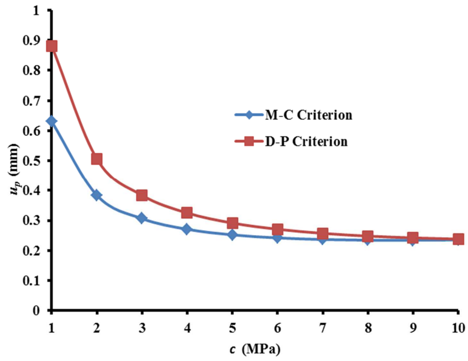


Fig.9 Influence of cohesion on displacement of borehole wall

3.3.2 Influence analysis of internal friction angle

Choose cohesion as 3MPa, change interval of internal friction angle is 10~55degree, original stress is 15MPa and the intermediate principal stress coefficient is 0.75, and obtain the change rule of relative radius of plastic zone and displacement of borehole wall with different cohesion are respectively shown as Fig.10 and Fig.11. It can be found from Fig.10 that the relative radius of plastic zone under M-C criterion and D-P criterion decreases with the increases of internal friction angle. After the internal friction angle is beyond 35degree, the differences of relative radius between M-C criterion and D-P criterion turn to be stable. And from Fig.11, it can be found that the displacement of borehole wall under these two kinds of criterions gradually decrease with the decreases in internal friction angle. While the internal friction angle is more than 35degree, the difference is very tiny between these two kinds of criterions. So taken together, the elastoplastic solution for M-C criterion and D-P criterion is basically consistent when the internal friction angle is more than 35degree, in the case that the other mechanical parameters of surrounding rocks is the same.

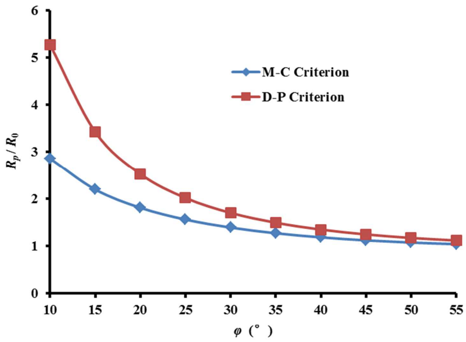


Fig.10 Influence of internal friction angle on relative radius of plastic zone

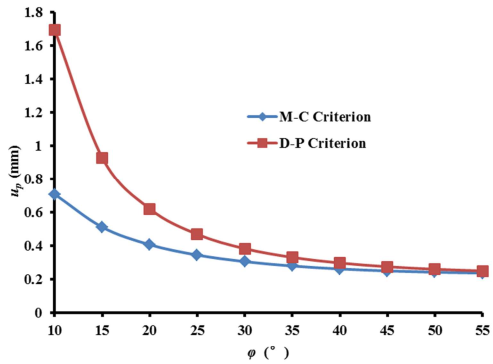


Fig.11 Influence of internal friction angle on displacement of borehole wall

3.3.3 Influence analysis of elastic modulus and Possion's ratio

From Eq. (14) and Eq.(35), it can be found that the relative radius is independent with elastic modulus and Possion's ratio, but the changes in elastic modulus and Possion's ratio can act on the changes in displacement of borehole wall, shown in Fig.12 and Fig.13. In order to further analyze these change rules, the influence of elastic modulus on displacement of borehole wall under the conditions of cohesion as 3MPa, internal friction angle as 30degree, intermediate principal stress coefficient as 0.75, change interval of elastic modulus as 50~4500MPa, and Possion's ratio as 0.3, is shown in Fig.11. And the influence of Possion's ratio on displacement of borehole wall under the conditions of cohesion as 3MPa, internal friction angle as 30degree, intermediate principal stress coefficient as 0.75, elastic modulus as 50~4500MPa, and change interval of Possion's ratio as 0.2~0.8, is shown in Fig.12.

From Fig. 12 and Fig. 13 it is not difficult to find, with the increase of elastic modulus, displacement of borehole wall gradually decreases. And in fact, the smaller the elastic modulus of coal body, the smaller the coal hardness, which means that the larger the displacement of borehole wall, the higher instable possibility the borehole, but M-C solution with D-P solution is little difference. With the increase of Possion's ratio, the displacement of borehole wall also increases, but D-P solution is much larger than M-Csolution, which means that the intervention of intermediate principal stress has effect on the increase of displacement of borehole wall.

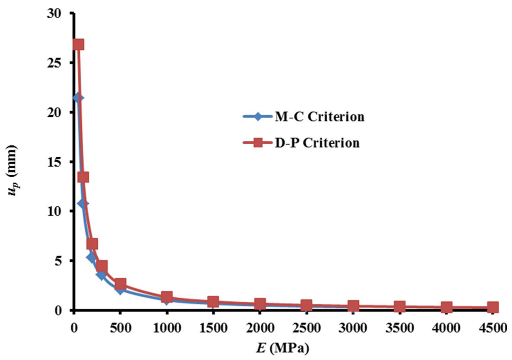


Fig.12 Influence of elastic modulus on displacement of borehole wall

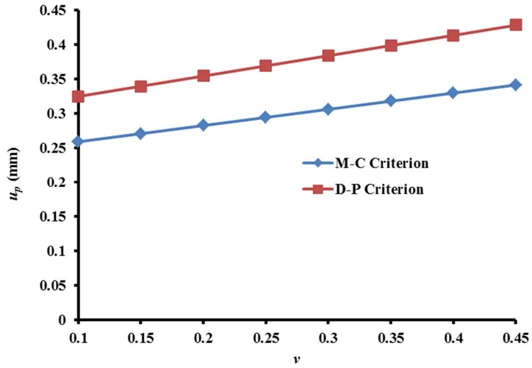


Fig.13 Influence of Possion's ratio on displacement of borehole wall

3.3.4 Influence analysis of original stress

The stress of surrounding rock in elastic zone of borehole is dependent on original stress. the influence of original stress on relative radius of plastic zone and displacement of borehole wall under the conditions of cohesion as 3MPa, internal friction angle as 30degree, intermediate principal stress coefficient as 0.75, change interval of original stress as 10~100MPa, are respectively shown in Fig.14 and Fig.15.

From Fig. 12 and Fig. 13 it is not difficult to find, with the increase of original stress, relative radius of plastic zone and displacement of borehole wall gradually increase. And the difference between these two criterions also gradually increases. Compared with the effect of inhesion and internal friction angle on relative radius of plastic zone and displacement of borehole wall, the effect of original stress is much obvious, especially the growth rate of D-P solution is much larger than the one of M-C solution. So the original rock stress conditions is the most critical factor for deform and failure of borehole. With respect to D-P criterion which considers the effect of hydrostatic pressure, but also considers the influence of intermediate principal stress, the M-C criterion is more conservative in the analysis of borehole stability, so D-P criterion may be appropriate to analyzethe borehole stability.

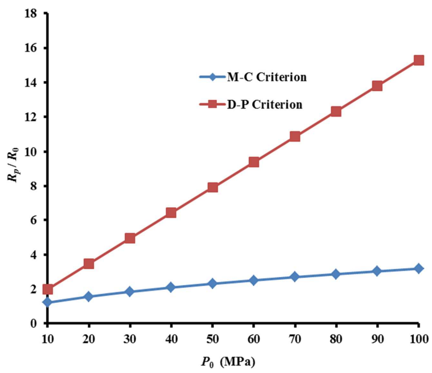


Fig.14 Influence of original stress on relative radius of plastic zone

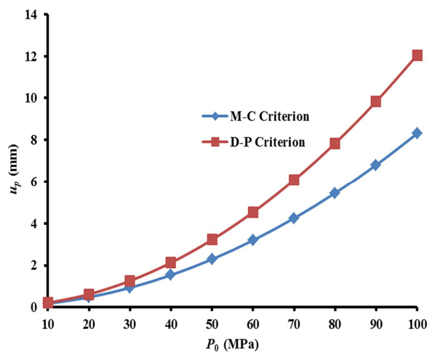


Fig.15 Influence of original stress on displacement of borehole wall

CONCLUSION

Under D-P criterion, the relative radius of plastic zone and displacement of borehole wall all decrease first and then increase with the increase of intermediate principal stress coefficient, which reach down to the minimum while the intermediate principal stress coefficient is equal to 0.75.

The distance away from the borehole wall to radial stress peak obtained in D-P criterion is much larger than the one of M-C criterion. And with the increases of internal friction angle and inhesion of coal mass, the relative radius of plastic zone and displacement of borehole wall under these two kinds of criterions all turn the decreasing tend. The changes in elastic modulus and Possion's ratio have nothing to do with the relative radius of plastic zone, but are related with the displacement of borehole wall. And the effect of elastic modulus and Possion's ratio vary in the opposite. In addition, the effect on M-C criterion solution and D-P criterion solution of original stress is the maximum.

M-C criterion is more conservative in the analysis of borehole stability, so D-P criterion may be more appropriate to analyze the borehole stability than M-C criterion.

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