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The Study of Rock Body Damage Constitutive Model in Multiple Fracturing

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Abstract

In order to characterize the mechanical behavior of rock body damage evaluation and forming multiple fractures, in this paper in multiple fracturing, we have established rock body damage evaluation constitutive model, and given the point that the rock can bear secondary damage in multiple fracturing. Established the secondary damage evaluation model, and obtained the method for calculating the parameter of the crack in multiple fracturing. We have verified the model by an oil well in Jilin oilfield, the result has fitted well with the actual engineering.

Key words: Multiple fracturing; Damage evaluation; Secondary damage

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INTRODUCTION

Refracture reorientation and crack formation are the key and bottleneck problem in the study of hydraulic fracture. In order to simulate and describe the initiation, propagation and geometric shape of crack actually, we must use damage and fracturing mechanics theory. Kachanov and Krajcinovic[1] proposed the initiation, propagation and converge of the micro crack can form macro crack. In this process, it cannot cause obvious plastic deformation brittle damage mechanism and nucleation, growing up and converge of the micro void, but it has obvious plastic deformation toughness damage mechanism. Valko, P.[2] simulated and analyzed the damage and cracking process of rock under the effect of hydraulic fracture using Kachan and PKN models, and he concluded that it has a damage weaken area at the crack tip. Yang Tianhong[3-5] applied the mesomechanics theory to material damage problem in the view of the nonhomogeneity of the medium. He proposed that the pore and crack is a network system which is combined by meso element. And he established the meso structural model that described the micro and meso deficiency structural morphology of the rock. Yuan Jianxin[6] have studied the rock problem using damage mechanics, and described the meaning and character of the rock damage from micro and macro aspect. Liu Hong[7] had analyzed the hydraulic fracture crack initiation and propagation mechanism based on fractal theory, damage mechanics and nonlinear dynamics combining the actual fracturing field. Liu Jianjun[8] had established hydraulic fracture damage mechanics model based on Gurson damage model, analyzed the damage effect of hydraulic fracturing on porous media by simple numerical simulation. Moreover, some scholars had studied some rock damage model. In this paper, we have used the variation of pore volume as the parameter to describe the rock damage, and defined new tensor damage variable, and established hydraulic fracturing rock medium damage deterioration constitutive model. And we have established the porosity and permeability evolution model based on damage theory. We have formulated finite element subprogram using the new and old methods, and packaged the subprogram into FEPG finite element software. And using the software to simulate an oil well at Xinmin region in Jilin oilfield, the numerical simulation results showed that the new method has better consistent than the old one.

1. THE CRACK EVALUATION OF MULTIPLE FRACTURING

In the process of multiple fracturing, the rock body with crack is under the condition of tension-shear stress, the plane crack extended and the relationship between extension force G and stress intensity factor can be described as follow.

$$G=\frac{1-\tilde{\mu}^2}{\tilde{E}}\int_0^a\left(K_{\mathrm{I}}^2+K_{\mathrm{II}}^2\right) \tag{1}$$

For the arbitrary single crack, the strain energy can be represented as follow.

$$üüüi= 2\int_0^a \quad \Omega=2\frac{1-\tilde{\mu}^2}{\tilde{E}}\int_0^a\left(\ {}_{\mathrm{I}}^{2}+\ {}_{\mathrm{II}}^{2}\right) \tag{2}$$

Integrating (1) and substituting it into (2), we can get (3).

$$U_d=\frac{1-\tilde{\mu}^2}{\tilde{E}}\left(K_{\mathrm{I}}{}^2+K_{\mathrm{II}}^2\right) \tag{3}$$

Assuming that in the process of multiple fracturing, it have *n* cracks in the rock propagating, and the rock body stain energy for the total cracks can be described as follow.

$$U_d=\sum_{\mathrm{m}=1}^{n}\frac{1-\tilde{\mu}^2}{\tilde{E}}\left(K_{\mathrm{I}}^{(\mathrm{m})2}+K_{\mathrm{II}}^{(\mathrm{m})2}\right) \tag{4}$$

For the process of multiple fracturing, the stress intensity factor of the crack is:

$$\begin{cases}\left(K_{\mathrm{I}}\right)=\dfrac{\lambda^*\sqrt{\pi a}}{2}\left[\left(1-\cos 2\vartheta\right)\left(\sigma_{\mathrm{xtotal}}\right)+\left(1+\cos 2\vartheta_{\mathrm{i}}\right)\left(\sigma_{\mathrm{ytotal}}\right)\right]\\ \left(K_{\mathrm{II}}\right)=\dfrac{\lambda^*\sqrt{\delta a}}{2}\left[\left(\sigma_{\mathrm{xtotal}}\right)\sin 2\vartheta-\left(\sigma_{\mathrm{ytotal}}\right)\sin 2\vartheta\right]\end{cases} \tag{5}$$

The second order stress tensor of the stress state σ_{ij} in the rock can be described as follow.

$$\sigma_{ij}=\begin{bmatrix}\sigma_{\mathrm{xtotal}} & \tau_{xy\mathrm{total}}\\ \tau_{yx\mathrm{total}} & \sigma_{\mathrm{ytotal}}\end{bmatrix} \tag{6}$$

Derivate the stress, and describe it in the form of tensor:

$$\frac{\partial u_d}{\partial\sigma_{ij}}=\frac{1-\tilde{\mu}^2}{\tilde{E}}\sum_{j=1}^{n}\left(\frac{\partial\left(K_{\mathrm{I}}\right)^{(\mathrm{m})}}{\partial\sigma_{ij}}+\frac{\partial\left(K_{\mathrm{II}}\right)^{(\mathrm{m})}}{\partial\sigma_{ij}}\right) \tag{7}$$

We can get (8) according to the damage theory.

$$\frac{\partial u_d}{\partial\sigma_{ij}}=C^{0-\mathrm{d}}\cdot\sigma_{ij} \tag{8}$$

According to the self-consistent theory and the stain of the crack, the damage flexibility tensor can be described as follow.

$$C^{0\text{-d}}=C^0+C^{\mathrm{d}} \tag{9}$$

Where, C^0 is flexibility tensor of the materials without damage; C^{d} is flexibility tensor of the materials with damage.

Substituting (9) into (7), we can get (10).

$$\left(C^0+C^{\mathrm{d}}\right)\cdot\sigma_{ij}=\frac{1-\tilde{\mu}^2}{\tilde{E}}\sum_{m=1}^{n}\left(\frac{\partial\left(K_{\mathrm{I}}\right)^{(\mathrm{m})}}{\partial\sigma_{ij}}+\frac{\partial\left(K_{\mathrm{II}}\right)^{(\mathrm{m})}}{\partial\sigma_{ij}}\right) \tag{10}$$

Substituting (10) into (5), we can get (11).

$$\left(C^0+C^{\mathrm{d}}\right)\cdot\sigma_{ij}=\frac{1-\tilde{\mu}^2}{\tilde{E}}\frac{\left(\lambda^*\right)^2\pi a}{4}\sum_{\mathrm{m}=1}^{\mathrm{n}}\left\{\begin{gathered}\frac{\left[\left(1-\cos 2\vartheta_{\mathrm{m}}\right)\left(\sigma_{\mathrm{xtotal}}\right)^{(\mathrm{m})}+\left(1+\cos 2\vartheta_{\mathrm{i}}\right)\left(\sigma_{\mathrm{ytotal}}\right)^{(\mathrm{m})}\right]^2}{\partial\sigma_{ij}}+\\ \frac{\left[\left(\sigma_{\mathrm{xtotal}}\right)^{(\mathrm{m})}\sin 2\vartheta_{\mathrm{m}}-\left(\sigma_{\mathrm{ytotal}}\right)^{(\mathrm{m})}\sin 2\vartheta_{\mathrm{m}}\right]^2}{\partial\sigma_{ij}}\end{gathered}\right\} \tag{11}$$

Substituting (6) into (11), we can get (12).

$$\left(C^0+C^{\mathrm{d}}\right)\cdot\begin{bmatrix}\sigma_{\mathrm{xtotal}} & \tau_{xy\mathrm{total}}\\ \tau_{yx\mathrm{total}} & \sigma_{\mathrm{ytotal}}\end{bmatrix}=\frac{1-\tilde{\mu}^2}{\tilde{E}}\cdot\frac{\left(\lambda^*\right)^2\pi a}{2}\sum_{\mathrm{m}=1}^{\mathrm{n}}\left\{A\cdot\frac{\partial A}{\partial\begin{bmatrix}\sigma_{\mathrm{xtotal}} & \tau_{xy\mathrm{total}}\\ \tau_{yx\mathrm{total}} & \sigma_{\mathrm{ytotal}}\end{bmatrix}}+B\cdot\frac{\partial B}{\partial\begin{bmatrix}\sigma_{\mathrm{xtotal}} & \tau_{xy\mathrm{total}}\\ \tau_{yx\mathrm{total}} & \sigma_{\mathrm{ytotal}}\end{bmatrix}}\right\} \tag{12}$$

Where:

$$\begin{cases}A=\left[\left(1-\cos 2\vartheta_{\mathrm{m}}\right)\left(\sigma_{\mathrm{xtotal}}\right)^{(\mathrm{m})}+\left(1+\cos 2\vartheta_{\mathrm{i}}\right)\left(\sigma_{\mathrm{ytotal}}\right)^{(\mathrm{m})}\right]\\ B=\left[\left(\sigma_{\mathrm{xtotal}}\right)^{(\mathrm{m})}\sin 2\vartheta_{\mathrm{m}}-\left(\sigma_{\mathrm{ytotal}}\right)^{(\mathrm{m})}\sin 2\vartheta_{\mathrm{m}}\right]\end{cases}$$

Equation (12) is damage constitutive relation.

2. THE ROCK BODY DAMAGE EVALUATION IN MULTIPLE FRACTURING

In the process of multiple fracturing, the total strain of the rock body can be described as follow,

$$\varepsilon_{ijtotal} = \varepsilon_{ij}^{0} + \varepsilon_{ij}^{d} + \varepsilon_{ij}^{ad} \tag{13}$$

Where, ε_{iiiii} is the total strain of the rock body; ε_{ij}^{0} is the strain of the rock body without damage; ε_{ij}^{d} is the initial damage strain of the rock body; ε_{ij}^{ad} is crack propagation strain of the rock body.

Using the generalized hook's law, the Equation (13) can also be described as follow.

$$\begin{aligned}\varepsilon_{ijtotal} &= \varepsilon_{ij}^{0} + \varepsilon_{ij}^{d} + \varepsilon_{ij}^{ad} \\ &= \left(\left[C^{0}\right]+\left[C^{d}\right]+\left[C^{ad}\right]\right)\sigma_{\text{reftotal}}\end{aligned} \tag{14}$$

Where, $[C^{ad}]$is additional flexibility damage tensor of the rock body with crack;$[C^{ad}]=f\,(a',a,k,m)$,k,m are the material parameters of the rock body.

According to the rock broken up experiments conducted by Athinson and Segall, the crack propagation can be described as follow.

$$\frac{R'}{R} = \left(\frac{a'}{a}\right)^{n} \tag{15}$$

Where, n is the crack propagation resistance increasing index, its value is 2/3 in general, a is the initial length of the crack, when it is at the initial stage of the fracturing, the length of the crack is perforation depth; a' is the length of the crack in the process of crack propagation; using the strain energy extension criterion, considering the effect of shear stress, the crack propagation length can be described as follow.

$$a' = a^{\frac{n}{n-1}}\left\{\frac{\pi}{ER}\left(1-\tilde{\mu}^{2}\right)\left[\sigma_{\text{reftotal}}^{2} + \tau_{\text{reftotal}}^{2}\right]\right\}^{\frac{1}{\text{n-1}}} \tag{16}$$

The damage tensor after the crack propagated can be described as follow.

$[C] = [C^{0}] + [C^{d}]f_{1}(a, k, m) + [C^{ad}]f_{2}(a', a, k, m)$

Where,

$$\left[C^{0}\right] = \begin{bmatrix} \dfrac{1}{\tilde{E}} & -\dfrac{\tilde{\mu}}{\tilde{E}} \\ -\dfrac{\tilde{\mu}}{\tilde{E}} & \dfrac{1}{\tilde{E}} \end{bmatrix}$$

Seeing from the above discussion, it can produce different crack propagation shape with different rock material and different tension shear stress state. The further propagation of the crack and the deterioration of the rock can be described by the damage tensor of the crack. The above is the rock body damage evolution regulation equation.

3. CASE STUDY

A block is selected, and the parameters of the block is as follows:

The maximum horizontal principal stress(s_{H}) is 32.0 MPa, the minimum horizontal principal stress (s_{h}) is 25.1 MPa, the bottom hole flowing pressure (P_{W}) is 3.0 MPa, the injection pressure (P_{O}) is 10.0 MPa, the young's modulus (E) is 28000 MPa, the critical damage strength (s_{c}) is 30.0 MPa, the wellbore radius (r_{w}) is 0.12 m, the external boundary radius (R_{0}) is 50.0 m, the fluid compressibility factor (a) is 0.8, the poisson's ratio (n) is 0.22, the matrix porosity (Φ_{p}) is 0.25, the fracture porosity (Φ_{f}) is 0.25, the internal friction angle (f) is 0.35 rad, and the softening modulus ($\tilde{E}$) is 800 MPa.

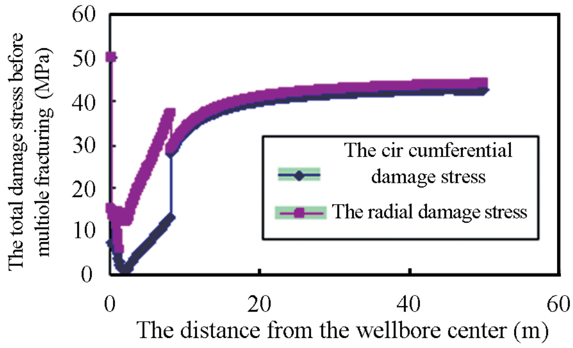

Figure 1
The Curve of Stress in Whole Region

The stress is much bigger with the farther distance away from the hole center in the area around the hole. When the distance reaches a certain distance (elastic region), the stress of borehole is equal to the formation of initial stress. The results coincide with the actual situation.

CONCLUSIONS

(a) Establish the model of calculating multiple fracturing micro crack damage evaluation dynamic and static stress intensity factor, and the model of the crack formation and rock nonlinear damage deterioration stress distribution in multiple fracturing. In the process of multiple fracturing, the rock in the damage region emerge secondary damage deterioration, and the filtration of fracturing fluid in the macro principal crack that have generated in the primary fracturing cannot be ignored.

(b) Simulate rock body stress distribution state in the process of multiple fracturing using finite element method, the result is in good agreement with the theoretical results. The new method has certain innovative and rationality.

(c) The constitutive model is mainly affected by the anisotropy of formation, effect of in-situ stress and the related rock mechanics parameters.

(d) The constitutive model can describe the crack propagation behavior of fractured rock mass in the process of multiple fracturing.

REFERENCES

[1] Krajcinovic, D. (1983). Constitutive equation for damaging materials. *J Appl Mech*, (50), 355-360.

[2] Guo, Q., Geehan, T., Swaco, M. I., Ullyott, K. W., & EnCana Corp. (1998). Formation damage and its impacts on cuttings injection well performance: A risk-based approach on waste containment assurance. *SPE 98202*.

[3] Yang, T. H., & Zhang, Z. (2002). Numerical simulation on the progressive processes of the wall rock's distortion failure caused by the excavating of footing groove. *Geotechnical Engineering Technique*, *11*(5), 293-296.

[4] Yang, T. H., Li, L. C., Tham, L. G., & Tang, C. A. (2002). Numerical approach to hydraulic fracturing in heterogeneous and permeable rocks. *Key Engineering Materia1s*, *46*, 351-356.

[5] Yang, T. H., Tham, L. G., Li, P. K., & Tang, C. A. (2004). Coupled analysis of flow, stress and damage in hydraulic fracturing. *Rock Mech. &Rock Eng*, *23*(24), 4254-4257.

[6] Yuan, J. X. (1993). Rock Damage Problems. *Rock and Soil Mechanics*, (1), 23-25.

[7] Liu, H., Zhang, G. H., & Zhong, S. Q. (2007). Analysis and research on key technologies hydraulic fracturing. *Drilling & Production Technology*, *330*(2), 49-53.

[8] Liu, J. J., Du, G. L., & Xue, Q. (2004). Discussion on continuum damage model of hydraulic fracturing. *Journal of Mechanical Strength*, *26*(s), 134-137.

[9] Cao, W. G., Mo, R., & Li, X. (2007). Study on statistical constitutive model and determination of parameters of rock based on normal distribution. *Chinese Journal of Geotechnical Engineering*, *29*(5), 671-675.

[10] Zhang, Y, Liao, H. L., & Li, G. S. (2004). A statistical constitutive model for rock continuous damage. *Journal of the University of Petroleum*, *28*(3), 37-39.

[11] Zhu, Q. Z., Hu, D. W., & Zhou, H. (2008). Research on homogenization-based micromechanical damage model and its application. *Chinese Journal of Rock mechanics and Engineering*, *27*(2), 266-272.

