Numerical Simulation of Crack Propagation in Hydraulic Fracture Using Extended Finite Element Method

Weicheng Wang[1]*, Wendong Li[2], Xiaoqing Guo[3], Shaohui Tang[3], Mingqing Huang[1]

[1]Fuzhou University, Zijin School of Geology and Mining,
Wulongjiang Road 2, Fuzhou 350108, China
*Corresponding Author E-mail: 211620020[at]fzu.edu.cn

[2]Serbia Zijin Copper Mine Co., Ltd,
Bor, Bor19210, Serbia

[3]Zijin Mining Group Co., Ltd.
Longyan364200, China

Abstract: ***In metal mines, hydraulic fracture is an important auxiliary caving technology to improve rock capability. To auxiliary design the hydraulic fracturing engineering parameters in Jama copper mine, Serbia, a numerical simulation is carried out. Using the extended finite element method (XFEM), a small-scale two-dimensional numerical model is built with ABAQUS software based on onsite of Jama copper mine. The crack propagation of hydraulic fractures under four schemes is simulated with variable in-situ stresses as the criterion. The results show that when the water injection rate is fixed, the magnitude change of in-situ stress affect the propagation of hydraulic cracks, and hydraulic cracks at -380m level are the most likely to expand, in addition, the expansion radius of the crack is 77.2 m, and the crack opening is 13.6 mm. This study auxiliary designs the hydraulic fracturing parameters and water injection section selection of BR ore body in Jama mine.***

Keywords: Hydraulic fracturing; XFEM; Numerical simulation; Parameter design

1.Introduction

Hydraulic fracturing technology is a commonly used method in the exploitation of shale gas, which was mostly used in oil exploitation and natural gas exploitation at first. The principle is to use water pressure to fracture the rock to form artificial fractures, and then allow the fractures to extend into the oil or gas reservoir to improve the fluid flow capacity in the reservoir, and finally through the supporting technologies of oil and gas flow in the production well to be exploited[1].With development of technology and in-depth study of reservoir geology, the application field of fracturing technology is also expanding, and it is widely used in oil field[2], shale gas field[3], coal mines[4] and other fields. In recent years, the large-scale mining technology of underground metal mines represented by the block caving method has been constantly improved. As an important auxiliary caving technology to improve rock cavability, the pre-conditioning by hydraulic fracturing has also received more and more attention and application[5].

It is of great theoretical significance to reasonably determine the engineering parameters of hydraulic fracturing in block caving mine, such as the burial depth of the construction section and the spacing of fracturing holes, to effectively improve the caving characteristics of ore rocks. The engineering parameters of hydraulic fracturing are mainly determined by theoretical calculation method[6], field test method[7], numerical simulation method[8], etc. The existing study provides a more effective means for the determining hydraulic fracturing engineering parameters. Lu et al[9]proposed a CSS mapping for the first time to characterize the oil supply capacity and reconstruction potential of reservoirs. CSS mapping is used to quickly determine fracturing parameters, including segment way, number of stages, number of perforating clusters, and fracturing fluid volume. Kao et al[10] built up the fracture-cavity carbonate geological models and simulated the hydraulic fracture propagation trajectory in fracture-cavity carbonate formation under different injection conditions. Based on the results, four optimization communication modes have been raised for fracture-cavity carbonate formation to auxiliary design the fracturing optimization and parameter optimization. The above research cases of hydraulic fracturing engineering parameter provide important is valuable for efficient production of mines.

Jama copper mine is a typical metal underground mine, Serbia. Jama deposit includes high-grade massive sulfide ore bodies and porphyry ore bodies, and the main mined ore bodies are BorskaReka (BR) and T3 ore bodies. The main BR ore body is a super-large porphyry copper ore body, with an occurrence elevation of+92 ~-934 m, a dip angle of 45 ~ 55°, a strike length of about 1450m, a width of about 360m and a vertical extension of about 1400m. In this study, four schemes are designed for the area between -210 m middle and -434 m middle of BR ore body under the condition of constant water injection rate of 300 L/min. Two-dimensional hydraulic fracture propagation at -230 m level, -280 m level, -330 m level and -380 m level are simulated by XFEM of ABAQUS software. Finally, according to the numerical simulation results, the optimal water injection section of hydraulic fracturing in Jama copper mine is determined, and the crack propagation radius and opening are predicted, which provides a technical reference for the hydraulic fracturing parameter design.

2.Mine overview

BR ore body is the main porphyry type copper ore body of Jama deposit, which is generally distributed along the Bor fault in the NW direction, which is a concealed deposit. According to geological drilling datas, the RQD value of rock quality index is 75%~92%, the RMR value is 70, and the uniaxial compressive strength is 111.19 MPa. It belongs to a mine with good rock integrity, good quality and poor collapsibility.

At present, stopes at -150 m level and above has basically completed mining, and -210 m level is under development. The ore body structure is mainly composed of reticulated fractures and 1 cm wide fractures, which are mostly filled and closed fissures. The main rocks in the mine are andesite and limestone, and the ore body is produced in altered andesite, mainly silicified andesite. The relevant rock mechanics parameters are shown in Table 1.

Table 1: Relevant rock mechanical parameters

Lithology	Uniaxial compressive strength σ_c/MPa	Uniaxial tensile strength σ_t/MPa	Elastic modulus /GPa	Poisson's ratio v
Silicified andesite	111.19	7.86	48.10	0.23

3.Numerical Simulation of structural parameters

3.1 Numerical simulation method

According to the current mining situation and the bottoming scheme, it is preliminarily determined that the hydraulic fracturing is carried out at the level of -210 m to -434 m, with a hole depth of 224 m, at -210 m horizontal drilling downward vertical drilling. Therefore, according to the obtained final mining range at the level of -434 m is measured, and it is finally determined that the range of parallel ore body strike of 850 m and vertical ore body strike of 350 m is the hydraulic fracturing construction area.

Considering the deep-hole hydraulic fracturing parameters in Northparks Copper Mine, Chuquicamata Copper Mine in Chile and other similar mines, the current mining situation and economic factors, staggered hole layout is adopted in the fracturing area, and the specific hydraulic fracturing pretreatment parameters are shown in Table 2.

Table 2: Hydraulic fracturing pretreatment parameters

Type	Value
Hole spacing parallel to ore body strike /m	80
Hole spacing perpendicular to ore body strike /m	120
Drilling diameter /mm	120
Number of boreholes	25
Drilling level /m	-210
Level buried depth /m	610

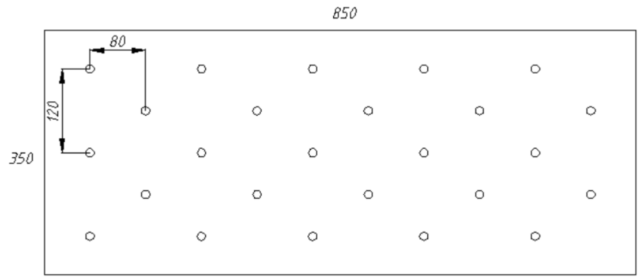


Figure 1: A layout of staggered hole

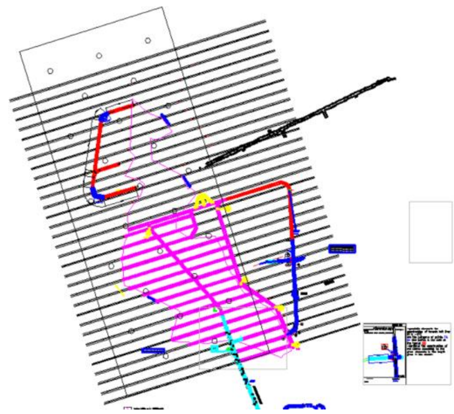


Figure 2: A drilling layout of BR ore body at -210 m level

Based on the convergence problem of XFEM simulation, this simulation does not consider the existence of dominant joints, and assumes that the rock mass is homogeneous and isotropic. The model is simplified to two-dimensional hydraulic fracturing simulation for a single hole. The water injection method adopts the injection of concentrated pore flow between nodes, and a fracture with a WN orientation and an included angle of 45° are preset to assist hydraulic fractures propagation. A two-dimensional planar model is built with ABAQUS software, which has a length of 160 m along the strike and a length of 160 m along the vertical strike. It is composed of 6400 quadrilateral elements, as shown in Figure 3.

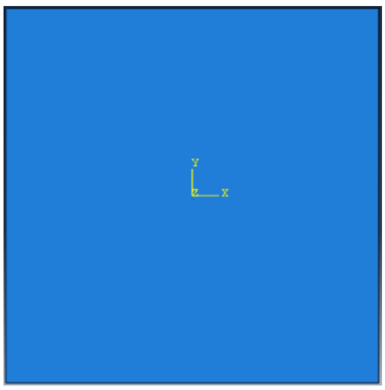


Figure 3: Schematic diagram of numerical simulation model of hydraulic fracturing

The loading process for simulation calculations consists of single or multiple steps. In the simulation of hydraulic fracturing, in addition to the initial analysis step included in the software, two analysis steps need to be added, Step 1 is used for in-situ stress balance and step 2 is used for fracturing operation. In Step 1, fixed constraints are imposed on the four boundaries of the model, while the pre-stress field and pore flow field are applied to the whole in the Initial Step. The water injection rate is fixed at 300 L/min, and the in-situ stress magnitude is changed. In the longitudinal direction, the level of -210 m to -434 m is divided into four levels for hydraulic fracturing simulation. The specific scheme is shown in Table 3.

The physical and mechanical parameters of medium are mainly the mechanical parameters of ore body, as shown in Table 1. The attribute assignment of ore body materials is shown in Table 4.

Table 3: Scheme main parameters

Scheme	Injection rate /L•min^{-1}	Level /m	In-situ stress		
			σ_{11} /MPa	σ_{22} /MPa	σ_{33} MPa
1	300	-230	16.7	18.0	13.7
2	300	-280	17.6	18.9	14.4
3	300	-330	18.4	19.8	15.1
4	300	-380	19.3	20.7	15.8

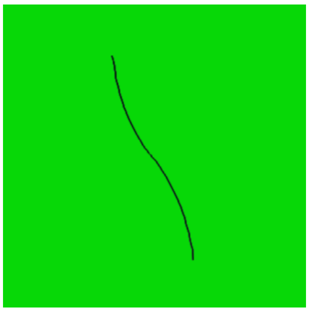
Table 4: Material attribute assignment

Material properties	Value
Maxps damage /MPa	35.29
Failure displacement	0.2
Damage stability viscosity coefficient	1E-06
Fluid leakage coefficient	1E-14
Gap flow viscosity	1E-06
Permeability	0.1

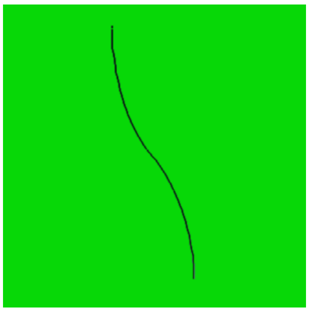
3.2 Results of numerical simulation

The displacement field and crack opening in hydraulic fracturing are analyzed, and the propagation law of hydraulic fractures is studied. Finally, the simulation results of each scheme are summarized, and the optimal water injection section is selected, which provides a reference for hydraulic fracturing parameter design.

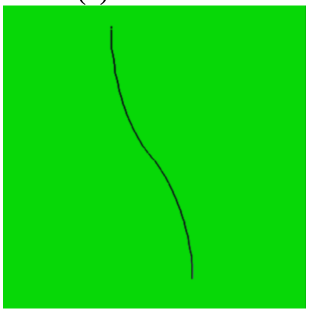
As shown in Figure 4, when the water injection rate is fixed at 300 L/min and the water injection lasts for 4~5 minutes, the hydraulic crack propagation radius at the -230 m level is relatively short, which is 56.5 m. The length of the hydraulic crack propagation radius at the -280 m level is greatly increased, which is 68.4 m. The propagation radius of hydraulic crack at -330 m level increases slightly, and the hydraulic crack propagation radius is 71.5 m. The hydraulic crack propagation radius length at -380 m level is 77.2 m, which is the longest.



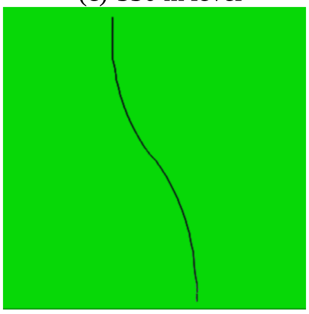
(a)-230 m level



(b)-280 m level



(c)-330 m level



(d)-380 m level

Figure 4: Two-dimensional fracture displacement diagram

From a lateral perspective, Origin mapping software is used to draw a line chart of the four levels and their corresponding radius of hydraulic crack propagation, as shown in Figure 5.

Obviously, when the water injection rate is fixed and the injection lasts for 4~5 minutes, with the increase of in-situ stress magnitude, the propagation radius of hydraulic crack tends to increase gradually. Among them, the -380 m level crack is the easiest to expand, with a propagation radius of 77.2 m, which is suitable for selection as the optimal water injection section.

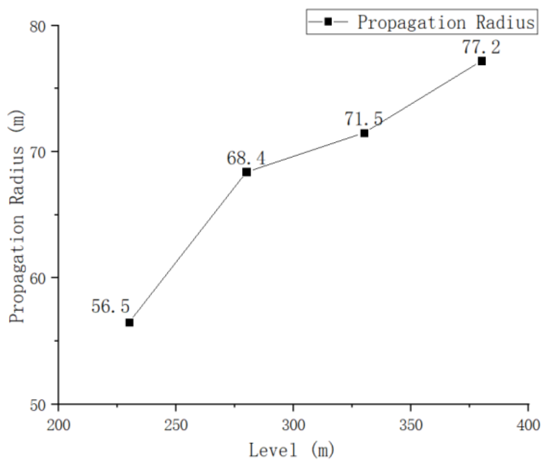


Figure 5: Level-Propagation Radius line chart

The result of the analysis step of the last step in Figure 6 shows that the crack opening at -380 m level and 300 L/min water injection rate for 5 minutes is 13.6 mm. The PFOPENXFEM field outputs the crack opening.

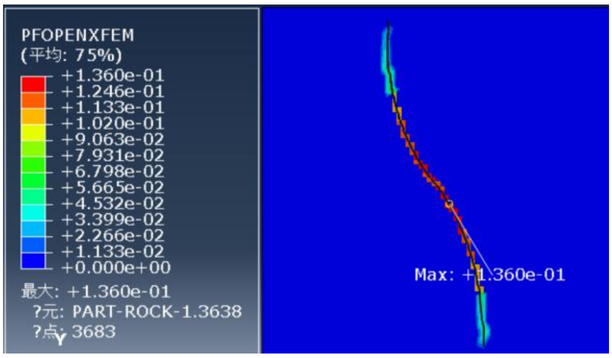


Figure 6: -380 m level crack opening diagram

4.Conclusions

1) The numerical simulation show that with the increase of in-situ stress magnitude and the deepening of buried depth, the propagation radius of hydraulic cracks tends to increase, of which cracks at the level of -380 m are the easiest to expand, with a propagation radius of 77.2 m and a crack opening of 13.6 mm.

2) The evaluation of numerical simulation shows the optimal water injection section is -380 m level, and the hydraulic fracturing parameters are 300 L/min in water injection rate, 80m in hole spacing parallel to ore body strike, 120 m in hole spacing perpendicular to ore body strike, 120mm in drilling diameter. The hydraulic fracturing effect carried out by this scheme is good, which auxiliary designs the hydraulic fracturing parameter and water injection section selection of BR ore body in Jama mine.

References

[1] Zhen Xu, Peng Lu. Current situation of domestic hydraulic fracturing technology [J]. Petrochemical Industry Technology, 2017, 24 (05): 280.
[2] Yikun LIU, Fengjiao WANG, Yumei WANG, et al. The mechanism of hydraulic fracturing assisted oil displacement to enhance oil recovery in low and medium permeability reservoirs [J]. Petroleum Exploration and Development, 2022, 49 (4): 864-873.
[3] Tong ZHOU, Haibo WANG, Fengxia LI, Yuanzhao LI, Yushi ZOU, Chi ZHANG. Numerical simulation of hydraulic fracture propagation in laminated shale reservoirs [J]. Petroleum Exploration and Development, 2020, 47 (5): 1170-1130.
[4] Bo Li, Zhen Shi, Li Li, Junxiang Zhang, Laisheng Huang, Yizheng He. Simulation study on the deflection and expansion of hydraulic fractures in coal-rock complexes [J]. Energy Reports, 2022, 8 (11): 9958-9968.
[5] Yuming Liu, Wen Li, Xin Wang, et al. Pretreatment technology of hydraulic fracturing ore and its application in block caving mines [J]. China Mine Engineering, 2022, 51 (03): 26-32.
[6] Guang Hu. Analysis of the influence of mechanical parameters of bedding shale on fracture morphology of hydraulic fracturing [J]. Drilling Engineering, 2022, 49 (02): 97-103.
[7] Yong Zhou. Determination of technical parameters and effect investigation of hydraulic fracturing in single thick coal seam [J]. Inner Mongolia Coal Economy, 2021 (23): 17-19.
[8] Xuemin Wang. Numerical simulation study on the influence of hydraulic fracturing parameters on roof fracture propagation [J].Datong Coal Science & Technology, 2020 (02): 14-16.
[9] Chunhua Lu, Hanqiao Jiang, Jinlong Yang, et al. Simulation and optimization of hydraulic fracturing in shale reservoirs: A case study in the Permian Lucaogou formation, China [J]. Energy Reports, 2022, 8 (11): 2558-2573.
[10] Jia-Wei Kao, Shi-Ming Wei, Wen-Zhi Wang, Yan Jin. Numerical analysis of the hydraulic fracture communication modes in fracture-cavity reservoirs [J]. Petroleum Science, 2022. 05. 011