Geotech Geol Eng
https://doi.org/10.1007/s10706-019-01041-6

ORIGINAL PAPER

Research on Application of Transient Electromagnetic Method in Hydraulic Fracturing

Dong-ming Zhang · Han Yang · Zi Rao · Zhong-yu Ou · Ping Tang

Received: 14 April 2019 / Accepted: 23 August 2019
© Springer Nature Switzerland AG 2019

Abstract Coal is China's dominant energy at present,but gas outburst occurs frequently in gassy coal mines, and it causes significant losses to people's lives and properties. Hydraulic fracturing is a valuable technology for gas permeability improvement in gassy coal mines. In this paper, the field experiment of hydraulic fracturing was conducted in a coal mine located in Yibin City, Sichuan Province. The transient electromagnetic instrument was applied before and after hydraulic fracturing respectively, combined with numerical simulation analysis of FLAC3D, aimed to estimate the influence scope of hydraulic fracturing. The numerical simulation results denote that the plastic zone principally distributes along the interface of the coal seam and roof due to the existence of stratification. Transient electromagnetic method analysis demonstrates that the coal-rock mass firstly cracks at 35 m and 41 m of borehole depth, the dominant fissure distribution range is in the interval of 33–50 m. And the influence area covers the range of 28–64 m, which means the influence scope is up to 36 m. It also reveals that it is feasible to determine the influence scope of hydraulic fracturing through transient electromagnetic method.

Keywords Hydraulic fracturing · Transient electromagnetic method · Numerical simulation · Influence scope

D. Zhang (✉) · H. Yang
State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, China
e-mail: zhangdm@cqu.edu.cn

D. Zhang · H. Yang
School of Resources and Safety Engineering, Chongqing University, Chongqing 400044, China

Z. Rao · Z. Ou · P. Tang
Shanmushu Coal Mine, Sichuan Furong Group Industrial Co., Ltd, Yibin 644500, China

1 Introduction

China's economy is in the period of sustained and rapid development at present, the demand for energies also increases substantially. Nowdays coal is still China's dominant energy (Yuan 2016). Coal resource exploitation is a comprehensive and complicated process, lots of coal mine disasters occurred during mining process due to complex geological environments and tough working conditions (Fan et al. 2017; Black 2019). Gas outburst is one of the most catastrophic disasters in coal mine, The total proportion of gassy mines and gas outburst incidents in China accounts for approximate 33% of that in the world (Huang et al. 2017). Gas outburst is a sophisticated coal mine gas dynamic phenomenon accompanied with a large amount of gas released from coal body in very short time, sometimes even coal would be brought out (Wang et al. 2018, 2019). Coal mine gas

Published online: 30 August 2019

outburst has caused great losses to people's lives and properties in the past few decades, it's a severe issue on coal resource exploitation and needs to be handle urgently (He et al. 2009; Fisne and Esen 2014; Hudecek 2008). Moreover, methane is non-renewable clean energy, therefore it's critical to facilitate gas extraction ratio and and promote gas utilization ratio to improve production status of coal mine and reduce gas outburst disasters (Wu et al. 2004; Xie et al. 2014).

Up till now, the commonly used technologies to improve gas permeability include pre-splitting blasting, hydraulic flushing and hydraulic cutting seam, etc. (Wang et al. 2014; Nesterova 2017; Shen et al.2018). Then hydraulic fracturing (HF) technology was introduced into coal mine field (Morgenstern and Sepehr 1991). In HF, the fracturing fluid (usually water) is continuously injected into coal seam through high-pressure pump. The coal seam would be crushed and develope lots of new fissures when the pressure of fracturing fluid exceeds coal seam strength. These fissures provide more channels for gas flow, thus the permeability of coal seam increases.

Some scholars have studied the application of HF technique on natural gases, petroleum and shale gas industry and found that it's effective for improving production (Wanniarachchi et al. 2019; Vishkai and Gates 2019; Nasriani and Jamiolahmady 2019). Moradi et al. (2017) investigated HF propagation process and its associated parameters in different conditions. Kang et al. (2018) performed field experiment in coal mine and obtained that HF in the main roof can substantially reduce abutment stresses. Szott et al. (2018) through numerical studies found that hydrofracturing can significantly enhance methane drainage of coal seams under appropriate parameters. Ni et al. (2018) carried out pulsating HF industrial experiments to improve the coal seam gas permeability and studied some physical properties, they concluded that the coal seam permeability coefficient increased by 48–217 times after the experiments. Li et al. (2019) proposed a new method of HF for low permeability coal seals in China, it can increase the effective water pressure so that can get better effects. Zhang et al. (2018) performed HF field experiment in a coal mine located in Sichuan, China, they acquired that the methane extraction rate of single fracturing borehole was approximately ten times larger compared to average extraction borehole.

Domestic and foreign researchers had contributed a lot to study HF technology and illustrated that it's a valid method for gas permeability improvement in coal mines. Hitherto, the main methods to determine influence scope are to analyze the water content of coal, the gas extraction area after HF (Wang 2019), tracer gas may also be used sometimes. While there are few literatures focus on the application of transient electromagnetic method (TEM) in HF realm, thus we concentrate on the appliance of TEM in HF field experiment in our study. In this paper, HF field experiment was conducted in a coal mine located in Yibin City, Sichuan Province. The transient electromagnetic instrument was put in use before and after HF respectively, the coal-rock mass main cracking area and influence scope of HF was finally determined combined with numerical simulation analysis. The objective of this research is to provide a new approach to gauge the influence scope of HF and figure out whether it's viable to measure HF influence area through TEM.

2 Theories Introduction

2.1 Water Motion Characteristics in Coal Seam

Hydraulic fracturing cracks the stratum by injecting high-pressure liquid (such as water), then continuously injecting water to extend the fractures further. The water injection process is actually an unsaturated permeation process.The general process is that the liquid firstly flows into preexisting fissures or weak planes, then facilitates to form secondary induced weak planes, and finally into micro fissures (Guo et al. 1993). The dominant water movement type in HF process is the permeation in fissures, diffusion in micropores and the capillary movement in pores., According to the mass conservation and permeability theory in high-pressure water injection process, it can be known:

$$\begin{cases} \mathrm{div}V = -\partial \Delta S / \partial t \\ \mathrm{div}V = k_1(P_1 - P_2) \\ V = -k_2 \mathrm{grad} P_1 \\ P_1 = w(P_1, \Delta S) \end{cases} \tag{1}$$

Where V is the permeation velocity of water in fissures; P_1 and P_2 is the water pressure outside and inside the coal respectively; ΔS is the increment of water content in coal; k_1 is the permeability coefficient of coal boundary; k_2 is the permeability coefficient related to water pressure in fissures.

Introducing dimensionless quantities φ and ω:

$$\varphi = \sqrt{a/k_3}x,\ \omega = (\alpha P_3/\Delta S_{\max})t \tag{2}$$

where a,α,k_3 represents the hydraulic parameter of coal; P_3 represents effective water pressure; $\Delta S_{\max}$ represents the maximum increment of water content in coal.

Once the boundary conditions are determined, the analytical solution can be obtained by the following equation:

$$Q = \Delta S_{\max}\sqrt{2k_3/a} \cdot \sqrt{\omega + \exp(-\omega) - 1} \tag{3}$$

where Q is the flow of water that expands in fractures.

Equations (2) and (3) show that during HF, the water flow in fissures is directly related to time, pump pressure, and coal seam geological conditions.

2.2 Transient Electromagnetic Method

TEM is also known as time domain electromagnetic method, it emits electromagnetic field into the ground through transienting coil, during the pulsed electromagnetic field interval (after power failure), it recieves the secondary eddy current field generated by underground media through an receiving coil or grounding electrode (Liu et al. 2005).

The basic working principle as follows: applying current to transmitting coil firstly to create primary magnetic fields around the coil, then interrupting the current suddenly, according to Faraday's law of electromagnetic induction, the induced electromotive force would be generated in conductive bodies under the ground or in coal mine, which in turn generates secondary induced current. Since the decay law of secondary magnetic field is related to the conductivity of underground geological body, the better conductivity, the lower decay speed (Yu et al. 2007). Therefore, the underground unfavorable geological body could be detected by studying the attenuation law of secondary magnetic field (Fig. 1)

The calculation formula of apparent resistivity of full-space transient electromagnetic method in coal mine is (Wang 2019):

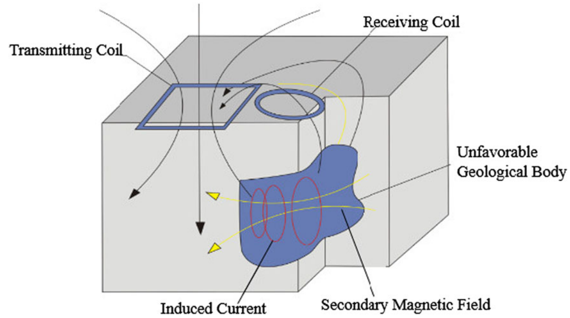


Fig. 1 Diagram of induced electromagnetic field conversion (Wu et al. 2018)

$$\rho = C \times \frac{\mu_0}{4\pi t} \times \frac{2\mu_0 SN^{2/3}}{5t(V/I)} \\ = C \times 6.32 \times 10^{12} \times (SN)^{2/3} \times (V/I)^{2/3} \times t^{5/3} \tag{4}$$

where C is full-space response coefficient; S is the area of receiving coil; N is the coil turn; t is attenuation time of secondary magnetic field; V/I is normalized secondary field potential value.

Due to the difference in conductivity, the apparent resistivity of fractured coal-rock mass is greater than that of intact coal-rock mass and water. Furtherly, the apparent resistivity of intact coal-rock mass is greater than that of water. Consequently, the coal-rock mass crushing zone and water-bearing zone can be identified from TEM detection results before and after HF respectively, thus the coal-rock mass crushing zone and influence scope of HF could be determined eventually.

3 Results Analysis

3.1 Geological Overview

The colliery is located in Yibin City, Sichuan Province. The coal belongs to anthracite from semi-dark to semi-bright, there are fissures and small faults in coal seam. The thickness of coal seam varies greatly in different districts and the gas concentration is high with relative gas emission rate of 10–15 m^3/t. The geological structures of coal seam are complex with dip angle of 4–32°. Coal seam thickness is 3.0–4.2 m with average thickness of 3.2 m. The hardness coefficient f of coal seam, immediate roof and floor is 2–4, 4–6, and 4–6 respectively. The roadways are constructed along the roof and there are two faults in this area. The hydrology situation is simple, there are no large water reservoirs on the ground, the water sources mainly come from meteoric water and the water filling in roof and fault fissures.

3.2 Hydraulic Fracturing Scheme

Through comprehensive survey and taking full account of the topography, attitude of stratum, construction conditions, obstacles, and other relative factors, two boreholes (1#, 2#) for HF were designed with diameters of 120 mm. The depth of 1# and 2# borehole is 43 m and 32 m respectively as shown in Fig. 2. The angle between 1# borehole and concentrated intake roadway is 3 degrees, so is 2# borehole.

After accomplishing the construction of 1# and 2# boreholes according to Fig. 2, the boreholes were sealed by the combination of hole packer and cement grouting, then high pressure water pump was adopted to inject water to boreholes to hydraulic fracturing (Fig. 3)

3.3 TEM Detection Results Analysis

The YCS800 transient electromagnetic instrument was used in this experiment. The main purposes were to figure out whether coal-rock mass was crushed before and after HF, whether developed extensive cracks. The water distribution area after HF was also a crucial problem to be solved. The measuring points were deployed adjacent to the top of 1# and 2# boreholes in crosscut for TEM detection, it covered the boreholes completely and close to the face-rib. A rectangular coil of 2 m $\times$ 2 m is equiped for transient electromagnetic instrument, the coil must keep the pace of measuring line when detecting. It's important to avoid the on-site equipments and devices that may impact the detection results as far as possible to reduce

Fig. 3 Hole packer installation

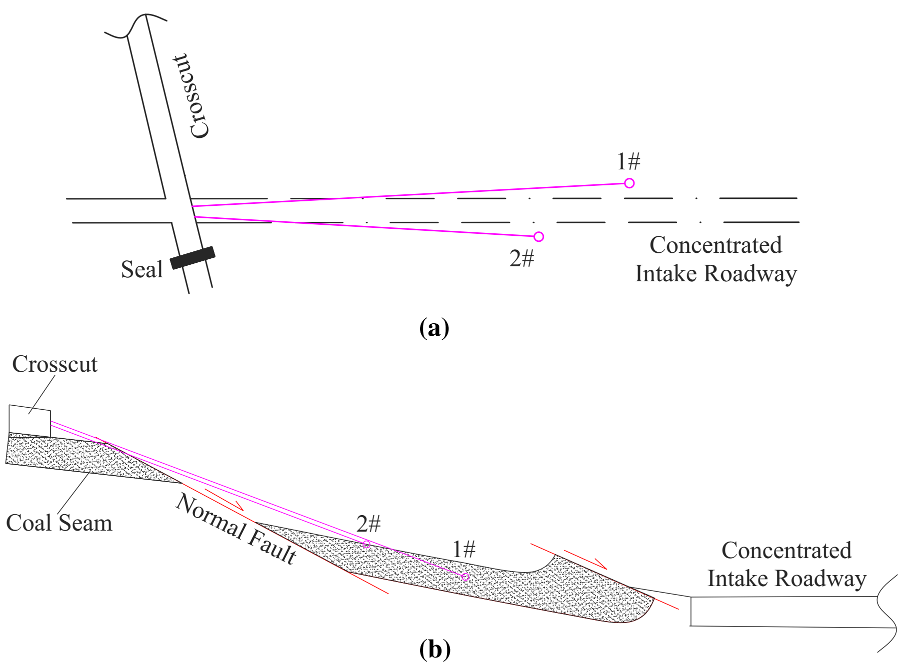


Fig. 2 Schematic diagram of borehole layout. **a** Plan. **b** Profile

errors. The pressure was 20 MPa and lasted for 4 h before being relieved in the course of HF. When the anchor nets,drilling machine, hydraulic supports and other equipments and devices that may have great impacts on TEM detection were removed, the YCS800 transient electromagnetic instrument was deployed for detection. The apparent resistivity before and after HF is shown in Fig. 4.

The previous scheme aimed to perform HF in both boreholes simultaneously. But in the initial stage of HF, the injected water sprayed out from 1# borehole due to poor quality of borehole sealing. Thus it could not proceed in 1# borehole any more but can be carried out smoothly in 2# borehole. So we ignored 1# borehole and only conducted HF in 2# borehole.

In the right part of Fig. 4b, the interval of 33–50 m expresses relative high apparent resistivity, which indicates that the coal-rock mass was crushed and fissures developed in this area after HF. It denotes that the dominant range of fissure distribution is between 33 and 50 m. Meanwhile, it also demonstrates that HF can crack the coal seam and increase gas seepage

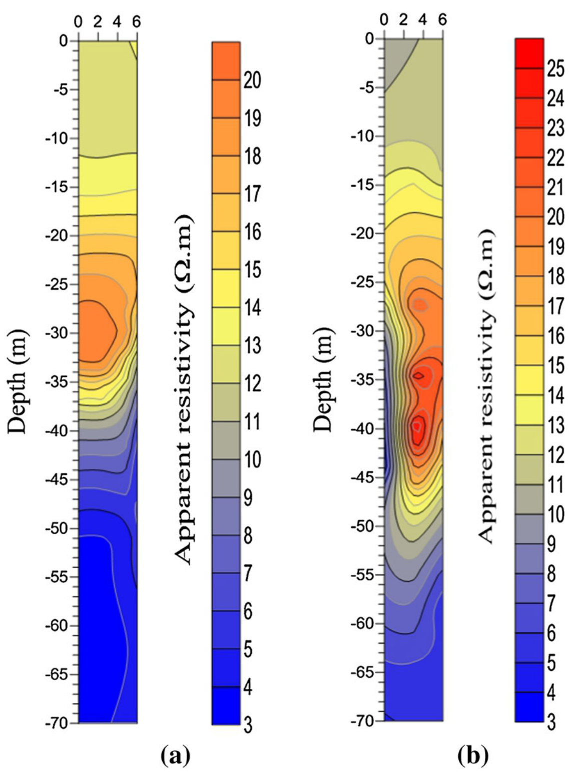


Fig. 4 The apparent resistivity. **a** Before hydraulic fracturing. **b** After hydraulic fracturing

channels to facilitate gas extraction. The apparent resistivity peaked at 35 m and 41 m respectively, it implied that the initial crack position is at 35 m and 41 m in this HF process, Furthermore, we can conclude that the coal and rocks were cracked badly and fissures developed substantially in the interval of 34–35 m and 39–42 m.

As shown in the left part of Fig. 4b, the apparent resistivity alters obviously from 28 to 50 m and it becomes smaller, it indicates that the water content of coal-rock mass increases massively after HF. Also, it reveals the water was mainly concentrated in the range of 28–50 m after HF. Between 50 and 64 m, the apparent resistivity becomes higher compared with that before HF, but smaller than that of the interval of 33–50 m, it demonstrates that the coal-rock mass gets wet in this area after HF.

Apparent resistivity decreases from 0 to 5 m after HF. It's because the injected water sprayed out from 1# borehole during the initial stage of hydralic fracturing, which made the coal-rock mass wet and led to decrease in apparent resistivity, it agreed with the practical situation of field experiment.

In summary, the coal-rock mass is crushed from 33 to 50 m after HF, and the dominant range of fissure distribution is in the interval of 33–50 m too. The apparent resistivity alters significantly from 28 to 64 m of borehole depth after HF with influence scope of 36 m. It also proves that it is feasible to determine the influence area of hydraulic fracturing through TEM.

3.4 Numerical Simulation Analysis

Numerical simulation analysis software FLAC3D was used in this experiment to analyze the effect of HF under two different borehole layouts. FLAC3D is an valuable numerical simulation software for geotechnical engineering. It can be used to study the mechanical properties of three-dimensional soil and rock mass or other materials, especially the plastic and rheological properties under yield limit. The built-in modules of FLAC3D can simulate the impacts on surrounding rock stress, strain and plastic zone, it's widely used in construction design, tunnel engineering, mining engineering and other relative fields. Numerical simulation physical and mechanical parameters (as shown in Table 1) were obtained based

Table 1 Numerical simulation parameters

Types	Bulk density (kg/m^3)	Elastic modulus (Gpa)	Bulk modulus (Gpa)	Shear modulus (Gpa)	Poisson ratio (–)	Cohesion (Mpa)	Friction angle (°)	Tensile strength (Mpa)
Sandstone	2487	13.5	5.97	6.01	0.123	2.06	40	1.13
Sandy mudstone	2510	5.425	2.56	2.36	0.147	2.16	36	0.75
Coal	1420	0.50	0.46	0.19	0.32	0.8	20	0.01

on the geological data provided by colliery technicians.

According to colliery geological data, the main roof is sandstone, the immediate roof and floor is sandy mudstone, the numerical model can be established in the light of the parameters in Table 1 (Fig. 5).

Numerical calculation was implemented through FLAC3D according to HF scheme, 1# borehole was located in coal seam, while 2# borehole was located at the interface of coal seam and roof.

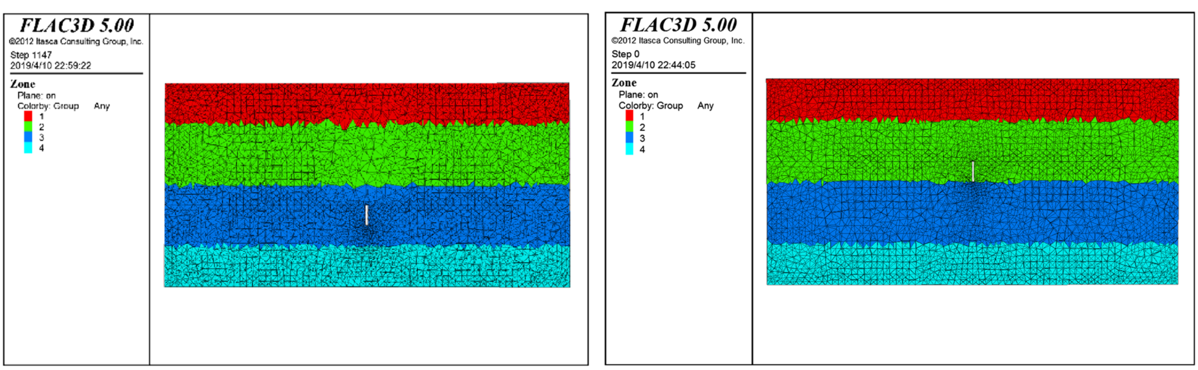
(1) 1# borehole numerical simulation results.

The numerical simulation was carried out according to HF scheme of 1# borehole. Figure 6a shows that in the first stage of HF, the plastic zone appears surrounding 1# borehole and expresses tensile and shear failure. Figure 6b reveals that the plastic zone gradually expands around the borehole as HF proceeding, and it mainly exhibits shear failure. The plastic zone begins to develop along the interface between coal seam and roof in large scales and mainly exhibits tensile failure. Figure 6d manifests that plastic zone in the interface expands to larger extents in later stage of HF. The roof and floor are also gradually damaged, and they are mainly characterized by shear failure and tensile failure respectively. Besides, the plastic zone has developed to the interface between coal seam and floor.

From all above we can conclude that during the whole HF process, plastic zone appears surrounding the borehole at first, then the interface between coal seam and roof, next the roof, and the floor at last. The largest area of plastic zone locates at the interface between coal seam and roof.

(2) 2# borehole numerical simulation results.

The numerical simulation was carried out according to HF scheme of 2# borehole. Figure 7a manifests that in the initial stage of HF, the plastic zone appears around 2# borehole and mainly exhibits shear failure. But the area of plastic zone is not as large as 1# borehole, it's because the strength of roof is higher than that of coal seam. Figure 7b illustrates that the plastic zone gradually expands along the interface between coal seam and roof as HF carrying on, and tensile stress dominants the plastic zone. As shown in



(a) (b)

Fig. 5 Diagram of numerical model. **a** 1# borehole. **b** 2# borehole

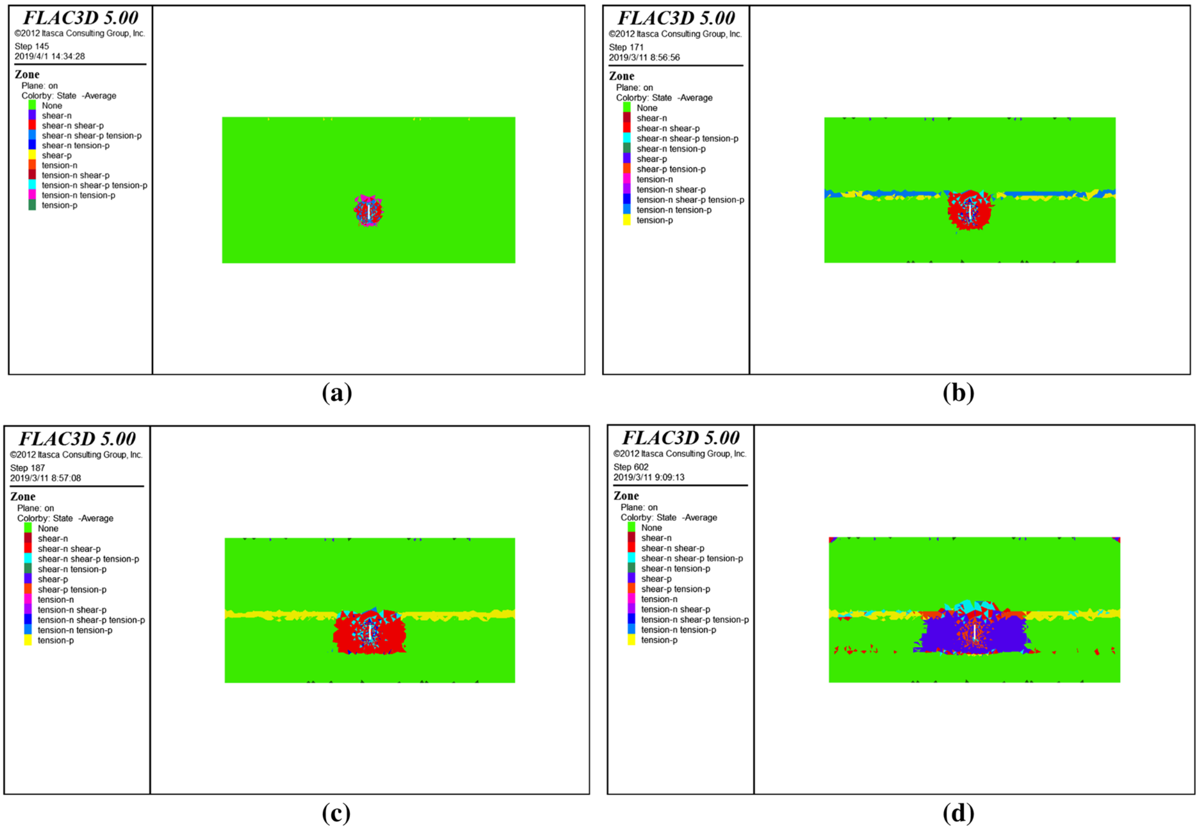


Fig. 6 Diagram of 1# borehole plastic zone evolution process

Fig. 7d, in the final stage of HF, the major crushing zone that surrounding 2# borehole is similar oval and the diameter of which is approximate 2.5 m, Addtionally, plastic zone comes up at the interface between coal seam and floor. It may result from the stress redistribution of surrounding coal and rocks caused by HF, in this situation, the weak planes begin to crush and crack, then the plastic zone follows.

In summary, numerical simulation results reveal that during the whole HF process, a small-scale plastic zone firstly appears around the borehole, then the interface between coal seam and roof, next the coal seam, the interface between coal seam and floor at last. The plastic zone obtains the largest acreage at the interface between coal seam and roof. The evolution process of plastic zone is relatively uniform in those areas with consistent lithology. If there were weak planes such as stratification, the plastic zone would expand more easily and get larger.

4 Discussion

The apparent resistivity of fractured coal-rock mass is greater than that of intact coal-rock mass due to the difference in conductivity. As shown in the right part (where 2# borehole located in on site) of Fig. 4b, the apparent resistivity was significantly larger than that before HF in the interval of 33–50 m. It denoted that the coal-rock mass cracked badly in this region. Combining the numerical simulation results in Fig. 7, the reason why apparent resistivity increased after HF may be that the end of 2# borehole located at the interaface of coal seam and roof, the stratification developed in the interface and expressed smaller strength, which led to crush and plentiful cracks in coal and rocks. Some time later after HF, the injected water diffused from the cracks, thus it manifests distinct increase in apparent resistivity.

While the left part (where 1# borehole located in on site) between 33 and 50 m poses substantially low apparent resistivity (Fig. 4b), It indicated that the

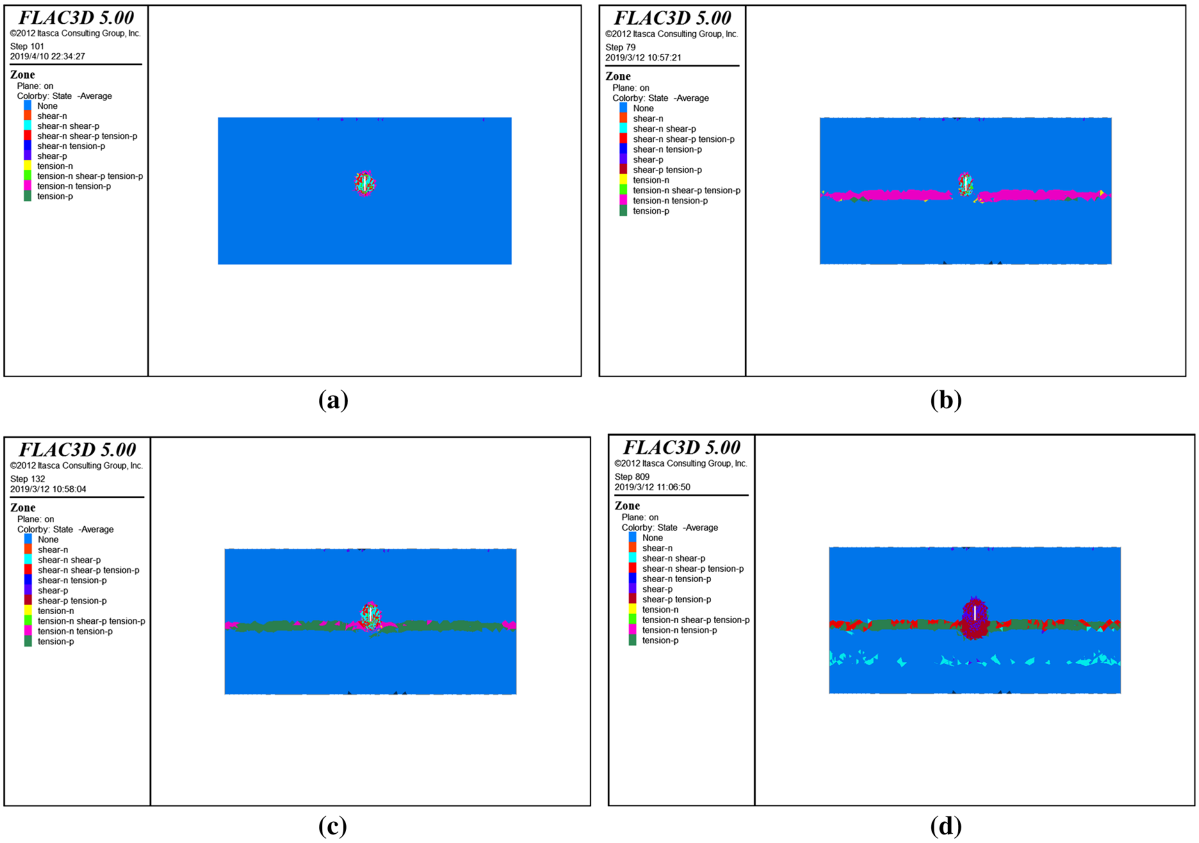


Fig. 7 Diagram of 2# borehole plastic zone evolution process

water content of coal-rock mass has greatly increased compared with that before HF. The reason may be that the end of 1# and 2# borehole located in coal seam and the interface between coal seam and roof respectively (Fig. 2). The relative altitude of 2# borehole was higher than that of 1# borehole, when the injected water of 2# borehole flowed along the interface to the location of 1# borehole, a part of which continued to flow by the interface, the others entered into 1# borehole. We didn't conduct HF in 1# borehole due to poor quality of hole sealing, thereby the coal-rock mass intactness was better relative to 2# borehole.When HF finished, the water that gathered in 1# borehole couldn't completely diffused instantly, it turned out the decrease in apparent resistivity.

Figure 4b manifested that in this experiment, the coal-rock mass was mainly crushed from 33 to 50 m after HF, but the apparent resistivity varied significantly in the interval of 28–64 m with influence scope of 36 m. It's because lots of micro cracks would be generated under continuous high pump pressure, then the water could be injected into those places anywhere micro cracks exsited. Thus, the influence area was not limited to 33–50 m but 28–64 m, which means the influence scope of this HF experiment was up to 36 m.

Combining the numerical simulation results of both boreholes (Figs. 6 and 7), we can found that in both cases HF has enormous impact on the interface of coal seam and roof, where the acreage of plastic zone is the largest. The reason for this phenomenon is that there are weak planes (such as stratification) in the interface of coal seam and roof, weak plane would shrink the strength of coal and rocks on account of its geological structure. When performing HF, it would be the first part to crush and the fissures propagate mainly along the weak planes. To some extent, the presence of weak planes may affect crack propagation even gas extraction effect.

The TEM detection results denote that the coal and rocks cracked intensely in the interval of 39–42 m (the dark orange section between 39 and 42 m in Fig. 4b), namely, the scope of coal-rock body major crushing zone is 3 m. The numerical simulation results indicate that the diameter of major crushing zone surrounding borehole is approximate 2.5 m (Fig. 7d). The error between TEM detection and numerical simulation results attributes to the inconsistency of practical site conditions and numerical model, in situ geological conditions is usually complex, it is hard and inaccessible to totally keep numerical model conditions the same as in situ conditions, it needs huge calculation and is always time-consuming, consequently the numerical mode is usually simplified and the error comes out inevitably, as long as the error can meet engineering requirements, it is acceptable. In this study, the scope of crushing zone that surrounding borehole acquired by TEM detection and numerical simulation is very close (3 m and 2.5 m respectively) and the error is small, thereby it is acceptable and can meet the experiment requirements. Meanwhile, the numerical simulation parameters stems from practical geological data, it testifies that the numerical simulation results is valid and reasonable. The numerical simulation results of HF through FLAC3D explained the analysis of TEM. It denotes that it is feasible to estimate the influence scope of hydraulic fracturing through TEM.

5 Conclusions

1. The initial crack point in coal-rock mass was at 35 m and 41 m of borehole depth in this hydraulic fracturing process. The dominant crushing zone and fissure distribution area was in the interval of 33–50 m, the influence scope of hydraulic fracturing in this experiment is 36 m
2. The numerical simulation results revealed that the plastic zone mainly distributed in the interface of coal seam and roof due to the existence of weak planes in both cases. The weak planes could be rationally utilized in scheme design to conserve energy and optimize hydraulic fracturing technique in practical application process.
3. The experiment results illustrate that it is viable to determine hydraulic fracturing influence scope through TEM, it provides a new approach to gauge the influence scope of hydraulic fracturing.

Acknowledgements This research was supported by the National Science and Technology Major Project of China (2016ZX05045-004) and Fundamental Research Funds for the Central Universities (No.2018CDYJSY0055).

Author's Contributions DZ and HY conceived and designed the experiments; HY and PT performed the field experiments; HY analyzed the data and wrote the paper; ZR and ZO provided the experiment site. All authors gave final approval for publication.

Compliance with Ethical Standards

Conflict of interests The authors declare that they have no conflict of interests.

References

Black DJ (2019) Review of coal and gas outburst in Australian underground coal mines. Int J Min Sci Technol. https://doi.org/10.1016/j.ijmst.2019.01.007

Fan CJ, Li S, Luo MK et al (2017) Coal and gas outburst dynamic system. Int J Min Sci Technol 27(1):49–55

Fisne A, Esen O (2014) Coal and gas outburst hazard in zonguldak coal basin of Turkey, and association with geological parameters. Nat Hazards 74(3):1363–1390

Guo F, Morgenstern NR, Scott JD (1993) An experimental investigation into hydraulic fracture propagation-Part 1 experimental facilities. Int J Rock Mech Min Sci Geomech Abstr 30(3):177–188

He TC, Li HG, Zhang HJ (2009) Gas drainage technology of high gas and thick coal seam. J Coal Sci Eng (China) 15(3):299–303

Huang WX, Liu DW, XIA M (2017) Study of meso-mechanism of coal and gas outburst. Chin J Rock Mech Eng 36(2):429–436

Hudecek V (2008) Analysis of safety precautions for coal and gas outburst-hazardous strata. J Min Sci 44(5):464–472

Kang HP, Lv HW, Gao FQ et al (2018) Understanding mechanisms of destressing mining-induced stresses using hydraulic fracturing. Int J Coal Geol 196:19–28

Li JT, Jia BS, Zhang CH et al (2019) Seepage mechanism technical practice of hydraulic fracturing of coal seam and auxiliary image simulation technology. J Vis Commun Image R 59:244–252

Liu SC, Liu ZX, Jiang ZH (2005) Application of tem in hydrogeological prospecting of mining district. J China Univ Min Technol 34(4):414–417

Moradi A, Nasriani HR, Rasouli V et al (2017) A comprehensive numerical study of hydraulic fracturing process and its affecting parameters. Geotech Geol Eng 35:1035–1050

Morgenstern NR, Sepehr K (1991) Time-dependent hydraulic fracturing in potash mines. Int J Rock Mech Min Sci Geomech Abstr 28(23):187–197

Nasriani HR, Jamiolahmady M (2019) Flowback cleanup mechanisms of post-hydraulic fracturing in unconventional natural gas reservoirs. J Nat Gas Sci Eng. https://doi.org/10.1016/j.jngse.2019.04.006

Nesterova SY (2017) Experience of destressing slotting to prevent gas-dynamic events in mechanized carnallite mining. J Min Sci 53(2):291–298

Ni GH, Xie HC, Li Z et al (2018) Improving the permeability of coal seam with pulsating hydraulicfracturing technique: a case study in Changping coal mine. China Process Saf Environ Prot 117:565–572

Shen RX, Qiu LM, Lv GG et al (2018) An effect evaluation method of coal seam hydraulic flushing by EMR. J Nat Gas Sci Eng 54:154–162

Szott W, Słota-Valim M, Gołąbek A et al (2018) Numerical studies of improved methane drainage technologies by stimulating coal seams in multi-seam mining layouts. Int J Rock Mech Min Sci 108:157–168

Vishkai M, Gates I (2019) On multistage hydraulic fracturing in tight gas reservoirs: montney formation, Alberta, Canada. J Pet Sci Eng 174:1127–1141

Wang XG (2019) Evaluation of underground hydraulic fracturing using transient electromagnetic method. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-019-04539-x

Wang YF, He XQ, Wang EY et al (2014) Research progress and development tendency of the hydraulic technology for increasing thepermeability of coal seams. J China Coal Soc 39(10):1945–1955

Wang CJ, Yang SQ, Yang DD et al (2018) Experimental analysis of the intensity and evolution of coal and gas outbursts. Fuel 226:252–262

Wang EY, Chen P, Liu ZT et al (2019) Fine detection technology of gas outburst area based on direct current method in Zhuxianzhuang Coal Mine, China. Saf Sci 115:12–18

Wanniarachchi WAM, Ranjith PG, Li JC (2019) Numerical simulation of foam-based hydraulic fracturing to optimise perforation spacing and to investigate effect of dip angle on hydraulic fracturing. J Pet Sci Eng 172:83–96

Wu CF, Zeng Y, Qin Y (2004) Present situation, application, and development of simultaneous extraction of coal and gas. J China Univ Min Technol 33(2):137–140

Wu G, Ai DC, Zou J et al (2018) Application of comprehensive detection technology in prevention and cure of coal mine water disaster. Coal Technol 37(11):141–143

Xie HP, Zhou HW, Xue DJ et al (2014) Technology and engineering of simultaneous exploitation of coal and gas in China. J China Coal Soc 39(8):1391–1397

Yu JC, Liu ZX, Liu SC et al (2007) Theoretical analysis of mine transient electromagnetic method and its application in detecting water burst structures in deep coal stope. J China Coal Soc 32(8):818–821

Yuan L (2016) Strategic thinking of simultaneous exploitation of coal and gas in deep mining. J China Coal Soc 41(1):1–6

Zhang ZX, Wang HT, Deng BZ et al (2018) Field investigation of hydraulic fracturing in coal seams and its enhancement for methane extraction in the southeast Sichuan Basin, China. Energies 11(12):3451. https://doi.org/10.3390/en11123451

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.