Rock failure mechanisms in the surrounding rock masses with deep level tunnels and in the source areas of disastrous events

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Experimental investigation on the non-planar propagation of hydraulic fracture in Fractured Shale Reservoir

Large-scale hydraulic fracturing technique was commonly used in the development of shale oil and gas reservoirs. The natural fracture and lamination have significant influences on the propagation of hydraulic fracture. Four shale outcrops with the dimension of 400×400×400 mm were selected to investigate the interactions between natural and hydraulic fracture by utilizing tri-axial fracturing test system and acoustic emission (AE) monitoring system. Experimental results indicated that hydraulic fracture will form a non-planar fracture network in space when it encounters the natural fractures (crossing or deflecting along the natural fractures). Natural fractures with big aperture or low bonding strength often cause a deflection of hydraulic fracture so that it is difficult to form a new principal hydraulic fracture. Fracture fluid flowing into the lamination distributed elliptically when hydraulic fracture penetrates the bedding plane. AE signal concentrates on the direction of crack initiation along the rock mass, while it is weaker as hydraulic fracture propagates along natural fracture. Therefore, whether hydraulic fracture could penetrate natural fracture is predominated by the fracture aperture and bonding strength of natural fracture. It is easy to form a spatial non-planar fracture network when hydraulic fracturing is conducted in fractured shale reservoirs. The volume of fracturing fluid penetrating into the lamination is less than that in principal hydraulic fracture. It is believed that the investigation on the interactions between hydraulic and natural fracture would be useful for prediction of the hydraulic fracture propagation and network hydraulic fracturing.

Key words: shale gas reservoir, hydraulic fracturing, non-planar propagation fracture network, volume fracturing.

Introduction

Multi-stage fracturing technology in horizontal well is a common means of reservoir stimulation in the development of unconventional reservoir. Intersection with geological discontinuities such as joints, bedding planes, faults and flaws in reservoirs might render fractures non-planar and multi-branch. Therefore, hydraulic fractures are very complex in randomly fractured shale reservoir.

Keshavarizi [1, 2] simulated the propagation of hydraulic fractures in fractured reservoir utilizing extended finite element method. In his research, the effects of the cohesiveness of the sealed natural fractures, the intact rock toughness and the pre-existing fracture geometry in hydraulic fracturing were studied, while the filtration of fracturing fluid along the fracture interface was neglected. Cheng [3] investigated the stress distribution and fracture mechanics for multiple parallel fractures in an infinite homogeneous reservoir using the boundary element model based on 2D displacement discontinuity method. The effects of fracture number and spacing were examined by modeling multiple sensitivity cases. Olson [4, 5] simulated the simultaneous propagation of multiple fractures based on pseudo 3D displacement discontinuity solution. In his research, the speed of fracture propagation was assumed to increase in proportion with the stress intensity factor at the fracture tip. Natural fractures were assumed to be equal-long and fluid pressure inside the hydraulic fracture was assumed to be a constant, which lead to the simulation unsuitable for hydraulic fracturing in real reservoir. On this basis, Sesetty [6] investigated the change of hydraulic fracture path, fracture aperture and pressure inside fracture in the process of fracturing fluid injecting. Rahman [7, 8] investigated the influence of pore pressure change on the intersection of hydraulic and natural fractures. He indicated that stress states, occurrence of the natural fracture and shear intensity are the dominant factors that affect the hydraulic fracture path. Zhao [9] assumed that when hydraulic fracture encounters natural fracture, a pair of first order fractures will form both on the left and right. Based on this network model, Li [10] investigated fracture width and fluid pressure distribution inside a hydraulic fracture with the change of fracture length, fracturing fluid viscosity and approaching angle. Weng [11] and Hou [12] established an unconventional fracture propagation numerical model with difference method. Their model assumed that the flow of the power law fluid inside the fracture is Poiseuille flow, and considered the size of fracture, the spreading of the proppant inside fracture network and the permeation of the fracturing fluid along the fracture interfaces. Kresse [13] and R.Wu [14] calculated the stress shadow of the branch fracture in the fracture network with an improved 2D displacement discontinuity method. They discussed the influence of stress shadow caused by the fracture which formed earlier on the propagation path of new hydraulic fractures, and applied it to the UFM model. Zangeneh [15] simulated the hydraulic fracture propagation in a naturally fractured rock mass using distinct-element method. He indicated that key interactions develop with the natural fractures that influence the stimulated reservoir volume through additional connected surface area and fracture dilation. These interactions also have the potential to decrease the size and effectiveness of the hydraulic fracture stimulation by diverting the injected fluid and proppant, and limiting the extent of the hydraulic fracture.

However, These researches above were carried out for the concrete specimens. The mechanical property of concrete specimen and the concrete sample with pre-existing fracture is very different with the mechanical property of real shale, which limiting the application of those research results in oilfield. In this study, to be more closer to the actual characteristics of shale rock, fractured shale outcrops in Longmaxi were selected to investigate the propagation of hydraulic fracture and interactions between natural and hydraulic fractures by utilizing tri-axial fracturing test system and acoustic emission monitoring system.

Experiment setup

Hydraulic fracturing simulation tests of the shale outcrops were conducted utilizing true tri-axial fracturing test system. Relative experiment parameters should be calculated using similarity criteria before testing. The mechanical parameters of Longmaxi shale formation: elastic module is 35 Gpa; Poisson's ratio is 0.25; pore pressure gradient is 1.05 MPa/100 m; the minimum horizontal stress gradient is 1.85 MPa/100 m; the maximum horizontal stress gradient is 2.1 MPa/100 m; overburden stress gradient is 2.0 MPa/100 m; reservoir depth is 2500 m. In hydraulic fracturing field, the initial pump rate stays 5 m^3/min to fracture the formation. Then the pump rate was enlarged to 10~12 m^3/min and all of these processes cost 200 min. The length of a single hydraulic fracture is about 250 m. The mechanical parameters of Longmaxi shale outcrop: elastic module is 40 Gpa; Poisson's ratio is 0.18. The size of rock sample is 400×400×400 mm. The length and diameter of the simulated wellbore is 140 mm and 16 mm respectively. The length of open hole is 60 mm.

Based on these basic data above, experiment parameters can be calculated as follows using similarity criteria. The minimum horizontal stress is 19.1 MPa; the maximum horizontal stress is 26.3 MPa; overburden stress is 22.1 MPa. During the process of fracturing experiment, a low pump rate with 0.163 ml/s was conducted to fracture the sample initially, then it was enlarged to 0.326 ml/s rapidly and injected for 25 seconds. Fracturing fluid used in experiment is slick water, the system of which is used in well site, and the viscosity was 2 mPa·s. The formula of slick water is shown in table 1.

Table 1

Formula of slick water fracturing fluid

Additives	FR-66	Optikleen WF	BE-9	Gasperm 1100
Function	Friction reducer	Viscosity breaker	bactericide	Water lock preventer
Concentration	0.075%	0.09	0.070%	0.2%~0.05%
Unit	Vol%	Kg/m^3	Vol%	Vol%

A total of four shale outcrop samples was selected in this study, as shown in figure 1. To observe the distribution of natural fractures easily before testing, they were marked using purple lines. To describe the interactions between hydraulic and natural fractures, the plane of shale samples was named as follows. The plane up and down was defined as P1 and P4 relatively; The plane front and back was defined as P2 and P5 relatively; The plane right and left was defined as P6 and P3 relatively. Since four outcrops comes from a same rock mass, every sample contains bedding fractures and bedding planes, shown in figure 2. In fracturing test, the sample 3# was monitored using acoustic emission system to investigate the propagation of hydraulic fracture. Six acoustic emission probes were used to get a more accurate result. The arrangement of the probes is shown in figure 2.

Fig. 1. Four shale outcrops (1#~4# from left to right)

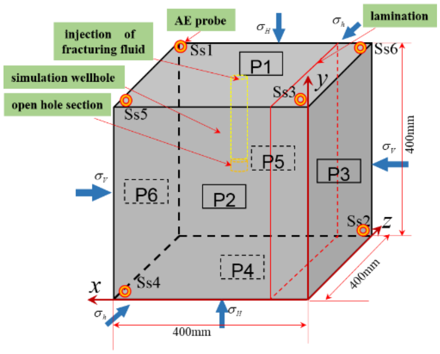


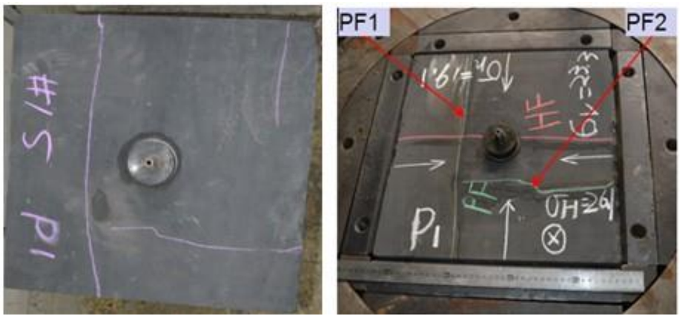
Fig. 2. Distribution of acoustic emission probes

Experimental results and analysis

The comparison of natural fracture morphology in shale outcrops before fracturing and the interactions between hydraulic and natural fractures after fracturing was displayed from table 2 to table 5. When encountering natural fractures, hydraulic fracture might either cross natural fractures (P1 in sample 1# and sample 3#) or deflect along natural fractures (P6 in sample 1#, P1 and P3 in sample 2#). Hydraulic fracture deflects along natural fracture initially and then propagates along the direction perpendicular to the minimum horizontal principle stress. Whether hydraulic fracture across natural fracture or not was not only related to in-situ stress and approaching angle [7, 8] but also to the natural fracture aperture and bonding strength. When hydraulic fracture encountered a series of small natural fractures, the overall direction of fracture propagation still keeps in the direction perpendicular to the minimum principle stress. Small natural fractures could only affect hydraulic fracture propagation in a local region. Hydraulic fracture initiation could not only be along natural fracture but also be along the direction of the rock mass, such as P1 in sample 3#, in which one wing of the hydraulic fracture initiated along natural fracture while another wing initiated along the rock. The direction of fracture initiation depends on the direction of the minimum fracturing pressure. Interactions between hydraulic and natural fractures would be more complicated and hydraulic fracture network is available when the density of natural fracture is high, such as P6 in sample 2#. The damaged region in P6 of sample 4# was filled with cement before testing. Due to the weaker bonding strength, the cement can easily detach from the rock mass under three-dimensional stress. Hydraulic fracture would deflect quickly when encountering the natural fracture with lager fracture aperture and lower bonding strength. Most fracturing fluid flowed out from P1 and no new fracture was observed in P3 for sample 4#, of which the complexity degree of hydraulic fractures is far less then sample 1# and sample 3#. Therefore, large faults should be avoided in oilfield fracturing, which can prevent the energy loss effectively caused by fracturing fluid flowing to the fault.

Table 2

Comparisons of fracture morphology of sample 1# before fracturing and after fracturing

Sample surface	Contrast diagram of fracture morphology before fracturing (left diagram) and after fracturing (right diagram)	Comparative analysis
P1		1. PF1 is a lamination throughout shale sample and PF2 is natural fracture. 2. HF propagates perpendicular to the minimum principle stress initially and then fractures lamination orthogonal to it. And then HF continues to propagate along PF1 and reach PF2. HF could penetrate PF1 and reach the end after increasing pump rate.
P3	 Green arrow indicates the direction of hydraulic fracture	There are two HFs on the surface. It illustrates that HF is likely to bifurcate in the process of HF propagation. But the overall direction of HF propagation remains be perpendicular to the direction of the minimum horizontal stress
P6		When encountering PF, HF will deflect initially and then penetrate PF. It continues to propagate perpendicular to the direction of the minimum horizontal stress.

Instructions: The purple lines in the left photograph represent natural fractures before fracturing. Due to the influence of some factors, such as the immersion of fracturing fluid, some color of the lines disappear. So the hydraulic and natural fractures are remarked. The red lines represent hydraulic fractures (HF) and the green lines represent primary natural fractures in the right photograph. σ_H is the maximum horizontal stress. σ_h is the minimum horizontal stress. σ_v is overburden stress.

Table 3

Comparisons of fracture morphology of sample 2# before fracturing and after fracturing

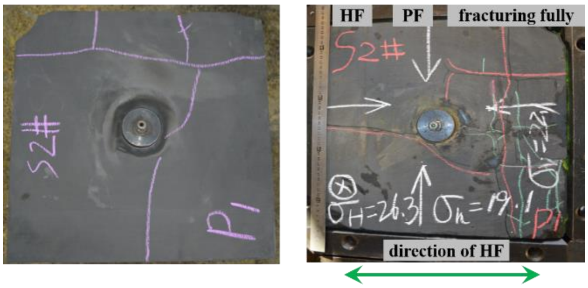
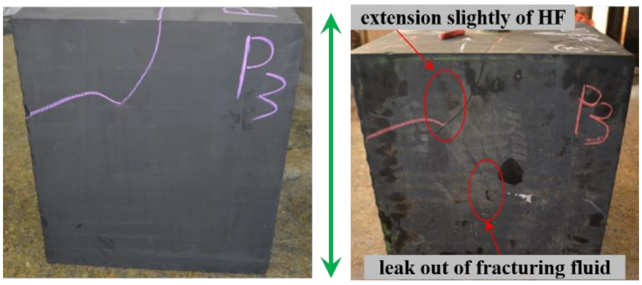
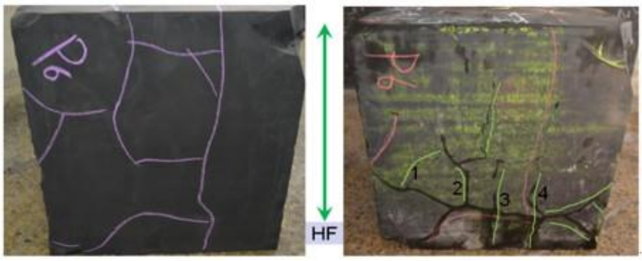
Sample surface	Contrast diagram of fracture morphology before fracturing (left diagram) and after fracturing (right diagram)	Comparative analysis
P1	 Green line represents hydraulic fracture (HF) and red line represents natural fracture (PF)	1. The left wing of HF propagates along PF. The right wing of HF propagates along the direction perpendicular to the direction of the minimum stress and then crosses natural fracture orthogonal to it with fracturing fluid flowing into natural fractures. 2. When PF encounters lamination at an angle of 90^0 approximately, fracturing fluid flows into the lamination and reach the end of sample later.
P3	 Green arrow indicates the direction of hydraulic fracture	HF propagates PF and PF could extend slightly with increasing the net pressure in PF. And then HF deflects along the optimal direction. Fracturing fluid flows out at the bottom of the sample, indicating that there are new fracture branches in the sample.
P6		It forms four approximately parallel main fractures in total, of which one is along natural fracture and others is new fractures. When the three new fractures meet a same PF, middle of which penetrates the PF while other two HFs stops propagation.

Table 4

Comparisons of fracture morphology of sample 3# before fracturing and after fracturing

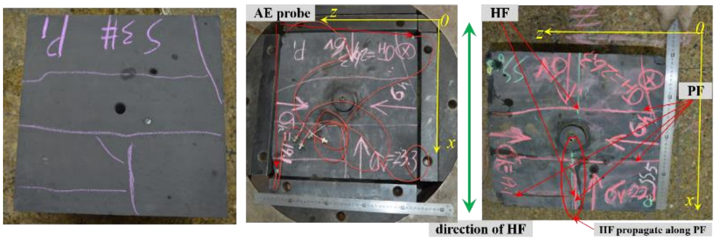
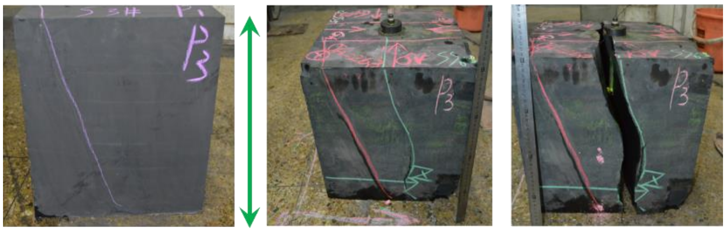
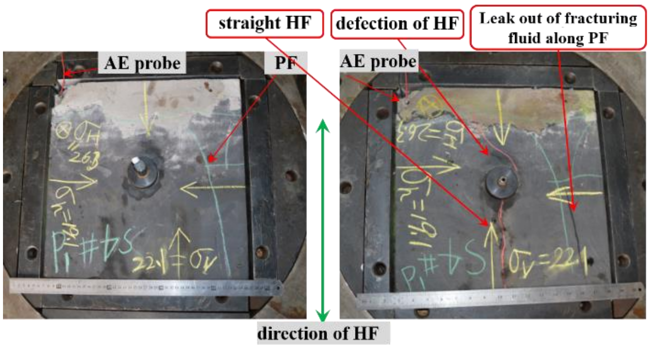
Sample surface	Contrast diagram of fracture morphology before fracturing (left diagram) and after fracturing (right diagram)	Comparative analysis
P1	 Green line represents hyraulic fracture (HF) and red line represents natural fracture (PF)	HF morphology is asymmetric fracture with double wings. one wing propagates along natural fracture and another wing fractures rock mass directly.
P3	 Green arrow indicates the direction of hydraulic fracture	HF propagates throughout the sample and the morphology of non-planar propagation is extremely evident. HF interconnects the left natural fractures along the lamination.
P6	 Green arrow indicates the direction of hydraulic fracture	The trace of HF can't be observed on the surface. But the main HF had been produced inside the sample and just not penetrate to the surface in fact.

Table 5

Comparisons of fracture morphology of sample 4# before fracturing and after fracturing

Sample surface	Contrast diagram of fracture morphology before fracturing (left diagram) and after fracturing (right diagram)	Comparative analysis
P1	 Red line represents hydraulic fracture (HF) and green line represents natural fracture (PF)	Due to the effect of the PF, one wing of HF deflects upward obviously. Fracturing fluid flows along the PF after entering the surface bonded with cement.
P3		No obvious hydraulic fractures on the surface
P6		The bonding strength between cement and shale sample is weaker and the cement is likely to detach from rock mass due to different deformation under three-dimensional stress.

Discussions

Longmaxi shale formation with enough lamination and natural fracture is anisotropic, which makes shale reservoir significantly different with sandstone reservoir. The interaction mechanism between hydraulic and natural fractures is extremely complex and also a scientific problem to be solved. A large number of hydraulic fracturing tests [16] have demonstrated that the mechanical properties of these structures and their occurrence could affect the propagation behavior hydraulic fractures. Non-planar propagation of hydraulic fracture will increase the degree of complexity, which is expected to reduce resistance migrated from shale reservoir to borehole.

For exporting shale reservoirs with developed natural fracture fully, the key of network fracturing is the need to improve net pressure in hydraulic fractures, making natural fractures or weak-surfaces open and forming more branches, increasing the interactions between hydraulic and natural fractures. Because of the anisotropy of shale reservoir, the stress applied on the hydraulic fracture during fracture propagation is not a single effect, but often a multiple fracture propagation problem in complex stress field. In large-displacement fracturing process rapidly, hydraulic fracture is likely to bifurcate when stress deflects or the microscopic structure changes in formation. Hydraulic fracture will continue to bifurcate due to the effects of displacement and natural fractures. Fracture bifurcation is related to the physical and mechanical properties and loading conditions. Fracture bifurcation propagation is available by changing the surface properties and control loading conditions, promoting forming network fracture.

As shown in tabl. 4, Hydraulic fracture communicated natural fractures and lamination, forming a non-planar fracture network. At present, Hydraulic fracturing design software in oilfield basically assumed that hydraulic fracture propagates in a plane, which is suitable for simulation of hydraulic fracture in homogeneous sandstone reservoir. However, the hydraulic fracture in Longmaxi shale reservoir is not a pair of symmetrical planar fracture but a non-planar network fracture, resulting that it is difficult to simulate the real situation of hydraulic fracture propagation in current hydraulic fracture prediction software. Although part of the research results in this paper displayed fracture propagation behavior in fractured shale reservoir, it is also a scientific problem to solve the fracturing mechanism and further research is needed. Suitable spatial network hydraulic fracture propagation model should be put forward and a simulation software of full three-dimensional non-planar hydraulic fracture should be designed to provide a technical reference for network fracturing design in fractured shale reservoir. Relevant research results will be introduced detailedly in my or my research team's academic papers.

Conclusions

Hydraulic fracture generally propagates along the direction perpendicular to the direction of the minimum principle stress. When encountering natural fractures, hydraulic fracture might deflect or continue to propagate after penetrating it. Whether deflection or penetration is related to the fracture aperture and bonding strength of natural fractures. The acoustic emission signal is concentrated along the direction of hydraulic fracture propagation from the rock mass and is weaker along the direction of natural fracture propagation. Internal natural fractures in rock sample should be described before monitoring hydraulic fracture propagation using acoustic emission system.

Small natural fractures can only affect the propagation of hydraulic fracture in local region. Natural fracture with big aperture and low bonding strength is likely to cause fracture deflection and fracturing fluid loss, making it difficult to form new main hydraulic fracture. Therefore, The developed section of fault should be avoided in oilfield fracturing treatment.

Hydraulic fracture is not a pair of symmetric planar fractures but a spatial non-planar fracture network in fractured shale reservoir. Hydraulic fracture deflection when crossing natural fracture and dynamic bifurcation of main fracture is the predominated factor for complicating the overall fracture morphology.

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