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Numerical investigation of the influences of rock fabrics on hydraulic fracturing operations

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Summary

The hydraulic fracturing (HF) technique has been used as a reservoir stimulation tool for more than six decades. During the last two decades, the increasing demand of hydrocarbons and the exploration of unconventional reservoirs spurred researchers to improve HF techniques and to better understand the stimulation process. HF enhances the connectivity of oil and gas bearing rock formations (e.g. shale) by fluid injection by creating an interconnected fracture network which increases the permeadilty resulting in an improved hydrocarbon production. Understanding the interaction between HF induced fractures and pre-existing rock fabrics is a major key to control and optimize stimulations. In this study, the combined finite element and discrete element method (FDEM) is utilized to numerically simulate HF and investigate the role of pre-existing fractures on the stimulated rock mass volume. Simulations suggested that at the local scale, HF driven fractures tend to propagate following the rock mass discontinuities, while at the reservoir scale, fractures tend to allign with the direction parallel to the maximum in-situ stress.

Introduction

In an HF operation, a pressurized fluid is injected through a wellbore into the oil and gas bearing formation with the scope of initiating and extending fractures into the reservoir (Jasinski et al., 1996). The injected fluid usually carries proppants, such as sand and glass beads, that have the aim to keep, together with induced shear displacements, the fractured formation from closing under the in-situ stress once the injection stops. This process increases the permeability of the formation, ultimately resulting in the economical production of hydrocarbons from unconventional reservoirs. At the same time, HF operations raise environmental and safety concerns as the injected fracking fluids could pollute groundwater (Osborn et al., 2011), and the HF process may activate natural faults, resulting in earthquake hazards (Healy et al., 1968). Therefore, it is of paramount importance that HF operations are carefully planned and monitored.

Field observation clearly show that in HF operation the fracture propagation direction is controlled by the orientation of the maximum principle stress and the local rock mass structure (Gale et al., 2007). However, conventional analysis tools typically assume the rock mass to be homogeneous, isotropic, and linear elastic thus resulting in HF induced fractures to be usually considered as bi-planar tensile cracks (Adachi et al., 2007; Dusseault, 2013). To capture the physics of discontinuous, heterogeneous and anisotropic reservoirs, techniques based on the Discrete Element Method (DEM) are well-suited because they inherently incorporate fabric features, such as faults and joints (e.g. Al-Busaidi et al., 2005). In this contribution, a two-dimensional (2D) FDEM code developed based on Munjiza et al. (1995), Munjiza (2004), Mahabadi et al. (2012), Lisjak et al. (2013), and Zhao et al. (2014) is utilized to study the interaction between HF and rock fabrics.

Theory and/or Method

FDEM is a hybrid numerical simulation method pioneered by Munjiza et al. (1995). It inherits the advantages of the finite element method (FEM) in describing elastic deformations and the capabilities of discrete element method (DEM) in capturing interactions and fracturing processes of solids (Munjiza, 2004). Basics of FDEM and fundamental governing equations can be found in Munjiza et al. (1995); Munjiza (2004); Mahabadi et al. (2012); Lisjak & Grasselli (2014) and are briefly summarized here.

A FDEM simulation uses a triangular FEM mesh to construct the model domain, which is discretized by introducing four-noded elements to each contacting triangular element pair (Mahabadi et al., 2012). The four-noded elements are termed as cohesive crack elements. Upon the application of forces, the cohesive crack elements can deform elastically and break when the shaer and/or tensile local diplacements are excessive.

In a 2D scenario, two fracture modes can be simulated by the cohesive crack element: Mode I, the tensile mode, and Mode II, the shearing mode. Failures involving both opening and shearing deformation components are classified as Mode I-II. When simulating the HF induced fracturing process, pressure is exerted on boundaries of broken joint elements to drive the propagation of fractures (Figure **1**). Natural rock mass discontinuities can be incorporated into FDEM models (Lisjak et al., 2014). For example, bedding planes can be implemented as weak interfaces, and pre-existing fractures can be simulated by removing cohesive crack elements from triangular element pairs along the fracture.

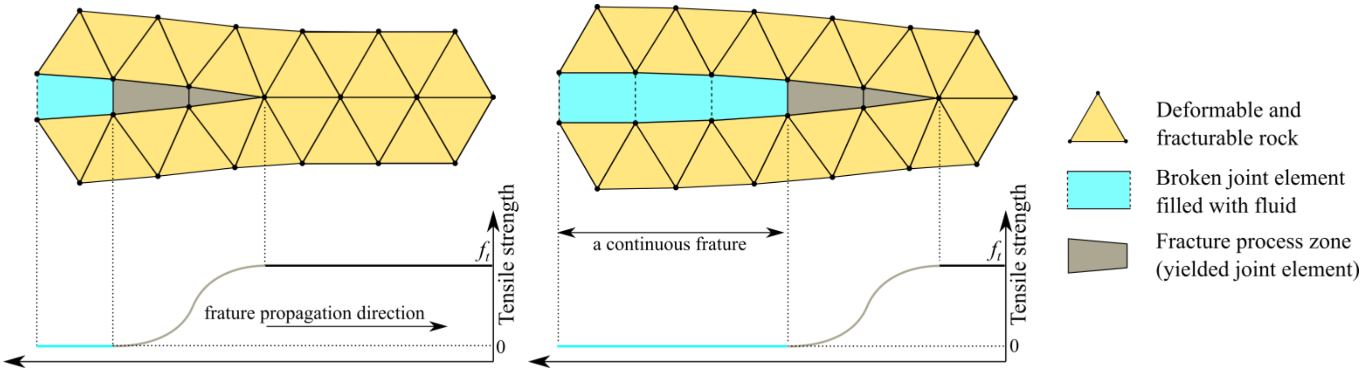

Figure 1. Schematic diagram of an HF-induced Mode I fracture propagates towards the east. The tensile strength of cohesive crack elements evolves from initial value (f_t) when the rock is intact to zero when the fracture is open. The continuous fracture consists of multiple broken cohesive crack elements.

Examples

Example 1: Influences of bedding planes

In this example, the *in-situ* stress conditions are σ_v = 65 MPa and σ_h = 50 MPa, which corresponds to a completion depth of about 2.5km. Horizontal bedding planes are implemented in the model. The dominant propagation direction of the fracture resulted to be aligned with the maximum principle stress direction; however, the model clearly shows that the presence of bedding planes greatly affect the fracture pattern (Figure **2**). Fractures penetrated into bedding planes adjacent to the main fracture, increasing the stimulated volume. The importance of bedding planes to HF is clearly highlighted by the FDEM simulation.

Example2: Influences of joint sets

This example is used to investigate HF operation in a formation with pre-existing joint sets. The same *in-situ* stress conditions as example 1 are used. Two joint sets inclined at ±45° to the directions of the principal stresses are embedded into the model (Figure 3).

The simulated fracturing pattern shows the crucial role of the pre-existing rock mass discontinuities. The emergent fracturing process consists of a combination of breakage through the intact rock and shearing along the pre-existing discontinuities. At the local scale, the fluid-driven fracture tends to follow the joints, while at the global scale, it tends to align with the maximum *in-situ* stress. Such results are in agreements with the conceptual geomechanical models such as in Dusseault (2013).

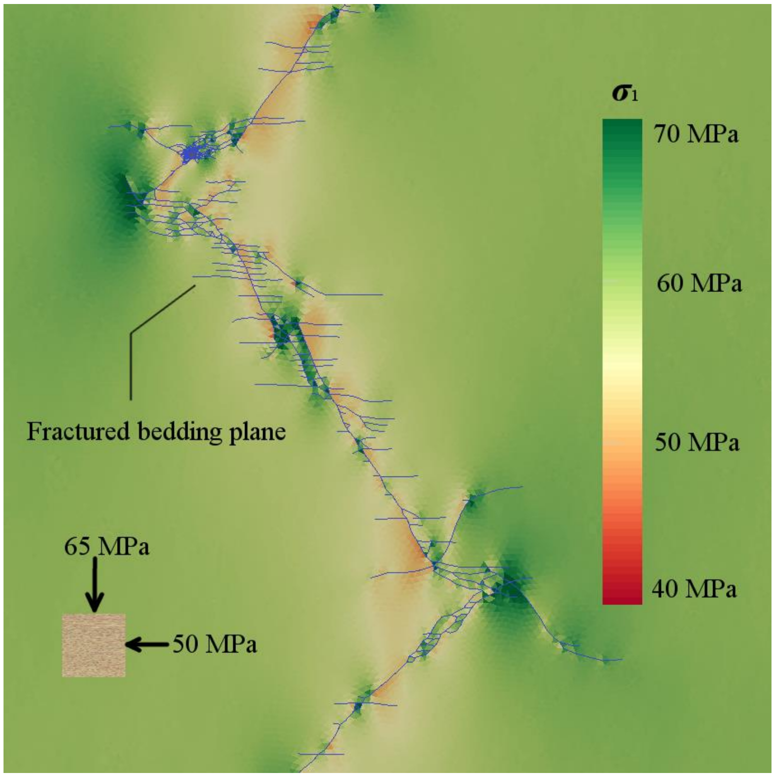

Figure 2. Simulated HF-induced fracture network and its interaction with the bedding planes. Background of the figure is the magnitude of the maximum principal stress (σ_1).

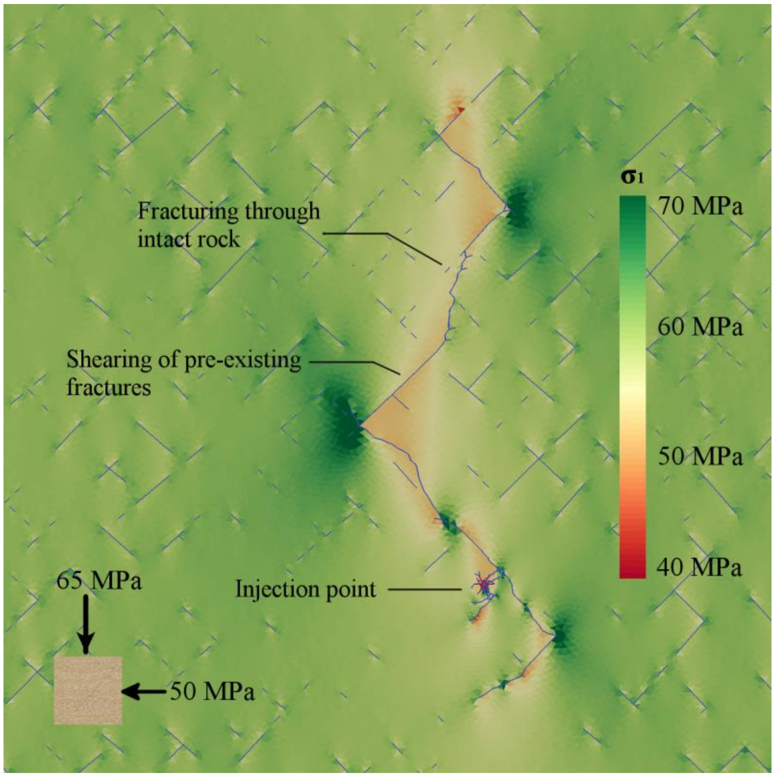

Figure 3. The interaction of the pre-existing fractures and HF induced fractures. The variation of the maximum principal stress (σ_1) is shown as background. Note the stress concentration at the tips of pre-existing fractures.

Conclusions

The results presented in this contribution prove that FDEM modeling technology is able to capture complex mechanical ineractions between HF and resevoir geology, and in particular the key role of natural rock mass discontinuities and bedding planes on the resulting stimulated volume geometry. Together with its proven ability in reproducing induced seismicity, FDEM unique ability in reproducing geomechanical processes makes it be one of the most promising HF modeling tools avaialble today.

Acknowledgements

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References

Adachi, J., Siebrits, E., Peirce, A. & Desroches, J., 2007. Computer simulation of hydraulic fractures. *International Journal of Rock Mechanics and Mining Sciences, 44*(5), 739-757.

Al-Busaidi, A., Hazzard, J. & Young, R., 2005. Distinct element modeling of hydraulically fractured Lac du Bonnet granite. *Journal of Geophysical Research: Solid Earth (1978–2012), 110*(B6).

Dusseault, M. B., 2013. Geomechanical aspects of shale gas development. *Rock Mechanics for Resources, Energy and Environment*, 39.

Gale, J. F., Reed, R. M. & Holder, J., 2007. Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments. *AAPG bulletin, 91*(4), 603-622.

Healy, J., Rubey, W., Griggs, D. & Raleigh, C., 1968. The Denver earthquakes. *Science, 161*(3848), 1301-1310.

Jasinski, R. J., Nelson, E. B. & Norman, W. D. 1996.

Lisjak, A. & Grasselli, G., 2014. A review of discrete modeling techniques for fracturing processes in discontinuous rock masses. *Journal of Rock Mechanics and Geotechnical Engineering, 6*(4).

Lisjak, A., Liu, Q., Zhao, Q., Mahabadi, O. K. & Grasselli, G., 2013. Numerical simulation of acoustic emission in brittle rocks by two-dimensional finite-discrete element analysis. *Geophysical Journal International, 195*(1), 423-443.

Lisjak, A., Mahabadi, O. K., Kaifosh, P. & Grasselli, G., 2014. A New Geomechanical Modeling Approach for Simulating Hydraulic Fracturing and Associated Microseismicity in Fractured Shale Formations. *ARMA e-Newsletter* (Special Issue: Geomechanics of Hydraulic Fracturing in Shale Formations), 9-12.

Mahabadi, O. K., Lisjak, A., Munjiza, A. & Grasselli, G., 2012. Y‐Geo: A New Combined Finite‐Discrete Element Numerical Code for Geomechanical Applications. *International Journal of Geomechanics, 1*, 153.

Munjiza, A. 2004. *The Combined Finite-Discrete Element Method*: John Wiley & Sons, Ltd.

Munjiza, A., Owen, D. R. J. & Bicanic, N., 1995. A Combined Finite-Discrete Element Method in Transient Dynamics of Fracturing Solids. *Engineering Computations, 12*(2), 145-174.

Osborn, S. G., Vengosh, A., Warner, N. R. & Jackson, R. B., 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *proceedings of the National Academy of Sciences, 108*(20), 8172-8176.

Zhao, Q., Lisjak, A., Mahabadi, O., Liu, Q. & Grasselli, G., 2014. Numerical simulation of hydraulic fracturing and associated microseismicity using finite-discrete element method. *Journal of Rock Mechanics and Geotechnical Engineering*.