ARMA 16-0284

# The Effects of Stress Changes and Natural Fractures on Hydraulic Fracture Interactions

Mack, M.G.
*Itasca IMaGE, Houston, TX, USA*

This paper was prepared for presentation at the 50th US Rock Mechanics / Geomechanics Symposium held in Houston, Texas, USA, 26-29 June 2016. This paper was selected for presentation at the symposium by an ARMA Technical Program Committee based on a technical and critical review of the paper by a minimum of two technical reviewers.

**ABSTRACT:** A fully three-dimensional hydraulic fracture simulator was used to demonstrate the impact of stress changes and natural fractures on hydraulic fracture network geometry. Propagating hydraulic fractures change the local stress field, affecting the trajectory of nearby fractures propagating simultaneously (e.g. in a multi-cluster stage) or sequentially (e.g. subsequent stages in the same or other laterals). This can induce fracture complexity even in a very simple stress regime with no pre-existing natural fractures. The paper also shows that the geometry of a natural fracture system can dominate the shape of the fracture network developed during hydraulic fracturing. It is essential to simulate fracture propagation in three dimensions to capture these effects accurately.

## 1. INTRODUCTION

Most hydraulic fracture simulators were initially developed to simulate the propagation of a single planar fracture from a vertical well. Their ability to model multi-stage, multi-cluster fracturing of horizontal wells is very limited because it is often added using approximations and empirical correlations. More recently, a general-purpose fully hydraulic-mechanically-coupled geomechanical simulator (Damjanac and Cundall, 2016) has been used to model these scenarios. This type of simulator, based on the Distinct Element Method (DEM), captures the effects of stress changes around complex fracture networks, including both the induced hydraulic fractures and natural fractures and faults (e.g. Mack and Zhang, 2016, Maxwell et al, 2016 and Leonard et al., 2016).

In the DEM-based simulator, the fracture trajectory is limited to the geometry of the pre-defined blocks in the model. It thus becomes very computationally challenging to model the propagation of fractures for which the fracture trajectory is unknown. Some solutions have been developed for two-dimensional problems (e.g. Olson, 2008, Cipolla et al, 2011), but these methods are not easily adapted to situations with dipping beds, slip on bedding planes, significant height growth or varying material properties.

Damjanac et al (2015) have described a simulator (XSite) which can be used to efficiently model fully three-dimensional fracture propagation. The simulator was specifically developed to model realistic hydraulic fracturing scenarios, including the interaction of multiple fractures with each other and with pre-existing natural fractures.

This paper presents the application of this simulator to typical field cases including zipper-fraccing and a case in the Horn River Basin in Canada with extensive natural fractures.

## 2. SIMULATOR HIGHLIGHTS

A few key features of the simulator used in this work are described below. More details can be found in Damjanac et al (2015).

The lattice-based simulator uses the concept of the Synthetic Rock Mass (SRM), in which the rock is represented by a particle-based model, and any pre-existing fractures are represented by a Smooth Joint Model (SJM). Fracturing of intact rock is represented by breakage of bonds (“springs”) connecting particles, and slip or opening of the segments of the SJM represents fracturing of the pre-existing fractures. The overall fracture system which develops thus captures the effects of interactions between the natural fractures (with pre-defined orientations) and the induced fractures (with no pre-defined trajectory).

## 3. MULTI-CLUSTER FRACTURING

Horizontal wells are often stimulated in stages by sequentially isolating small sections (e.g. 300 ft) of the wellbore and fracturing each isolated section by pumping at a high rate into a small number of perforation clusters (e.g. 3 to 5). Typical continuum models of single stages show the effect of a "stress shadow", in which the outer clusters tend to take most fluid and the inner ones take very little. As a result, a few dominant outer fractures develop, and the interior ones die out. If perforation friction is relatively high, then the fluid distribution is more uniform and the middle fractures are more extensive, either laterally or due to out-of-zone growth.

Lee at al (2016) have described the application of a calibrated model of a hydraulic fracture treatment in the Horn River Basin in Canada. The lattice-based simulator is used here to model one 3-cluster stage of that treatment. In this first example, the initial principal stresses are constant in the entire model, there are no pre-existing fractures or Discrete Fracture Network (DFN), and the effect of gravity is neglected. An isolated fracture would thus grow radially outward from the perforation cluster.

Figure 1 shows the results of modeling this stage with the lattice-based simulator. Initially, the three fractures grow roughly uniformly because the stress field around each one is not affected significantly by the others. However, as the fracture radius becomes approximately equal to the cluster spacing, the stresses are affected and the fractures from the two outer clusters propagate outward from the center of the cluster. The fracture from the middle cluster is somewhat suppressed on the top, but grows further down than the outer fractures. In addition, it develops a relatively complex branched shape, due to the stress changes around it.

Although the plan view (Figure 1) suggests that the fractures are very wide, the outer two are actually bowl-shaped, and the inner one is relatively narrow (Figure 2).

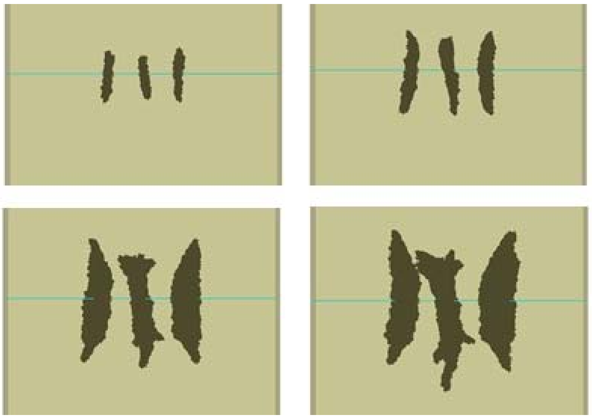

Fig. 1. Temporal evolution of three-cluster fracture geometry.

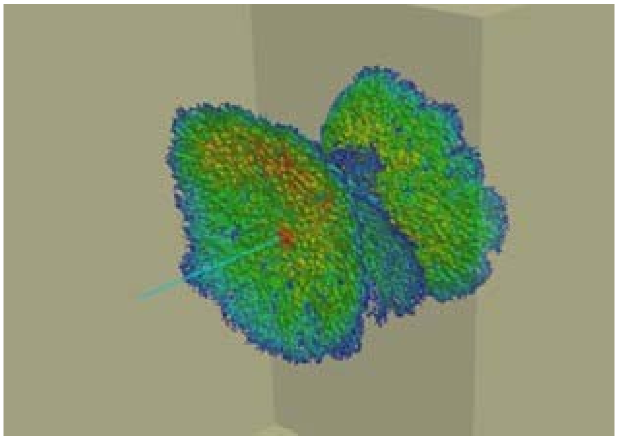

Fig. 2. Fracture aperture in three-cluster fracture.

This very simple example demonstrates that fracture complexity can develop even in the absence of pre-existing fractures.

## 4. ZIPPER FRACTURING

Zipper-fracturing is an operational technique in which multiple laterals are stimulated together. Operational efficiency is improved if one lateral can be prepared for the next stage (e.g. plugged and perforated) while another is being fractured, because waiting time between stages is reduced. Commonly, two (or more) laterals from a single pad would be zipper-fractured.

In this example, there is only one fracture in each stage, representing a well with a sliding-sleeve completion. Figure 3 shows the fracture geometry at the end of each of four stages of pumping (two in each well).

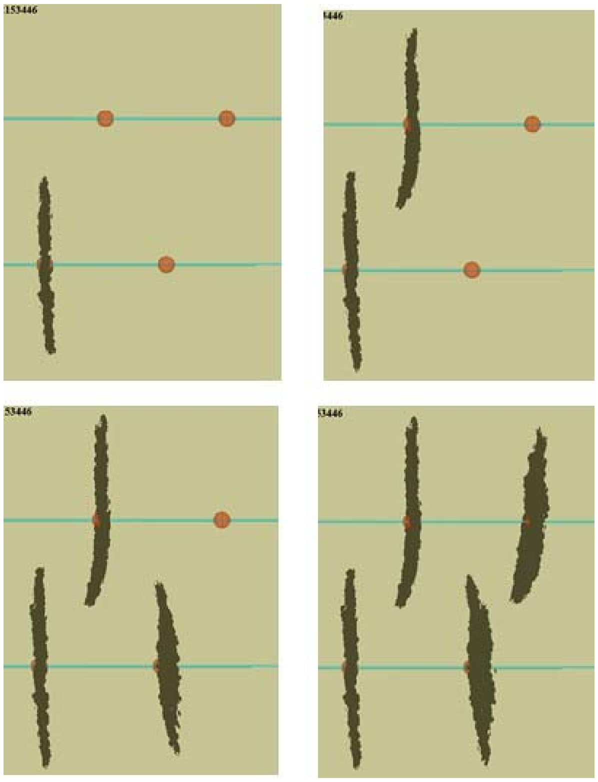

Fig. 3. Fracture geometry during zipper-fracturing operation.

The tips of later fractures have a tendency to be attracted towards the previous fracture, and it should also be noted that fractures continue to propagate after pumping ends, for two reasons, i.e., the energy still stored in the system with relatively low leakoff, and the stress changes induced by the later fractures.

Figure 4 shows the results of a similar simulation in which the order of fracturing was changed. In this case, fracturing of the first well got ahead of the second, such that the first fracture in the second well was placed between the two fractures in the first well. The second fracture shows the bowl-shaped stress shadow effect seen in the multi-cluster case. However, the first fracture in the second well is much more linear in this sequence because it is propagating along a plane of symmetry between the two previous fractures.

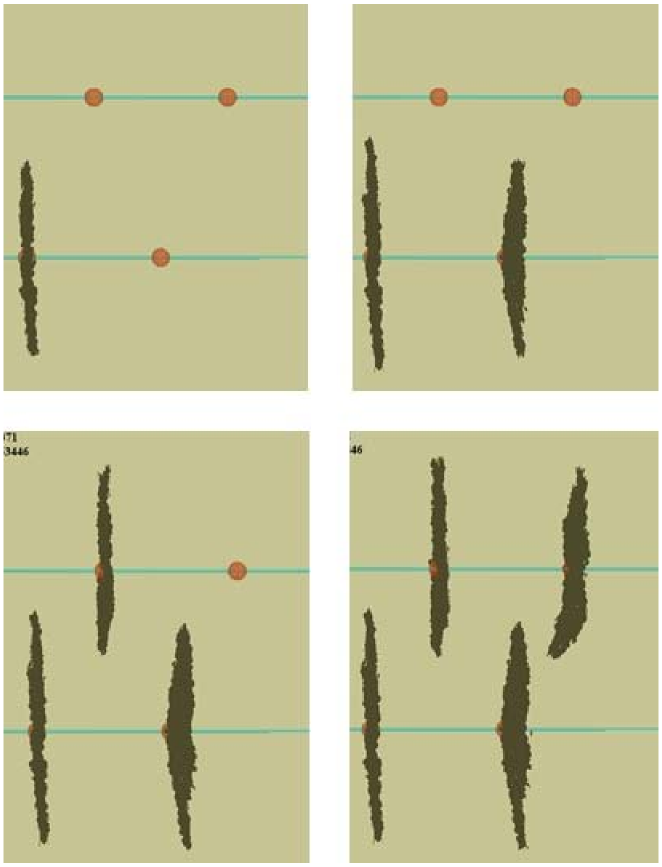

Fig. 4. Fracture geometry during zipper-fracturing operation

Figures 3 and 4 show that fractures may be attracted to, or repelled from previous fractures, depending on the spacing between them. This is consistent with laboratory results reported by Bunger et al. (2011)

The orientation of the stress field is not always well-known and the fractures are not transverse to the wellbore. In these cases, it is possible that the intended zipper-fracture could actually become a tip-to-tip fracture. In order to compare more directly with the previous zipper-frac examples, this is simulated here by offsetting the fracture initiation points, such that the initiation points are aligned and the fractures propagate tip-to-tip.

Figure 5 shows that the first pair of fractures connect, but the other two do not, due to the stress shadow effect. Figure 6 shows the results of the same model, with sequential fracturing. In this case, the stress changes appear to cause the first fracture connection to be more tenuous and the second pair to connect.

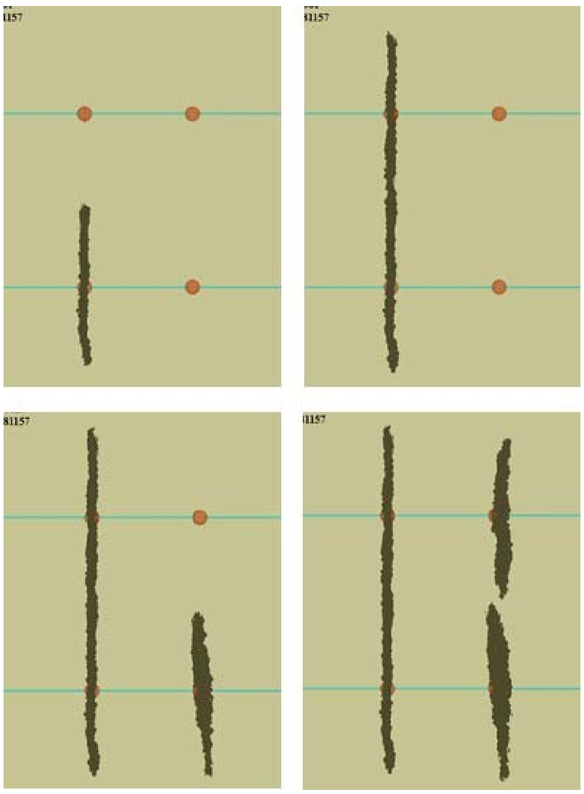

Fig. 5. Fracture geometry during tip-to-tip- zipper-fracturing.

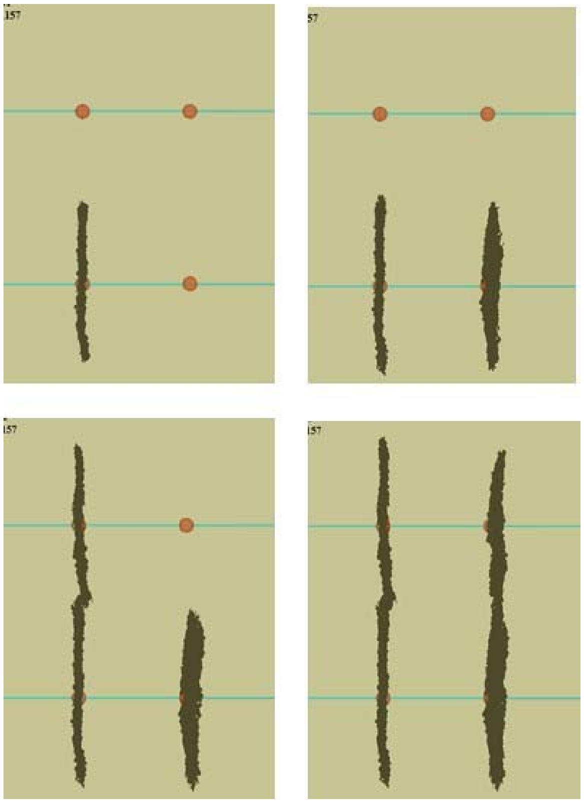

Fig. 6 Fracture geometry during tip-to-tip sequential fracturing

Figure 7 compares the fracture aperture for these two tip-to-tip cases. Although the fractures appear to be connected in Figure 6, the connection is quite poor for sequential fracturing. This highlights the importance of considering the full three-dimensional nature of the problem.

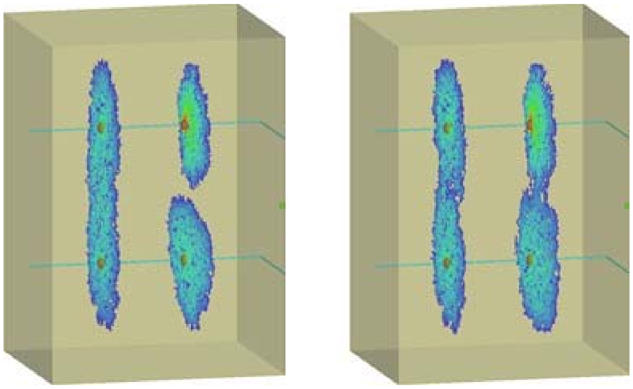

Fig. 7 Fracture aperture comparison after tip-to-tip fracturing.

## 5. THE EFFECT OF NATURAL FRACTURES

It is commonly believed that natural fractures increase fracture network complexity and enhance production. In this section, we use the Horn River Basin case study to demonstrate the impact of the DFN on the final results.

Figure 8 shows the fracture geometry at the same times as Figure 1 for the case with no DFN. When the induced fractures propagate into a pre-existing fracture, the fluid tends to flow into the natural fracture until it reaches the end of the fracture segment and then propagate out from the natural fracture until it reaches another one. This is more readily observed in Figure 9, which shows that the aperture is greatest near the wellbore and in a few of the natural fractures, indicating that for this sub-parallel natural fracture network, a significant proportion of the fluid migrates into the natural fractures.

The map view of these fractures (Figure 8) suggests that the DFN *increases* the planarity of the fracture because it is both vertical and sub-parallel to the preferred plane of propagation of induced fractures. When the natural fractures are sub-vertical or oriented further from the preferred fracture plane, the tendency to follow them can increase complexity as well as increase microseismic activity (e.g. Chorney et al, 2016).

## 6. CONCLUSIONS

A fully three-dimensional lattice-based simulator has been used to model the complex fracture geometries developed during hydraulic fracture stimulation of horizontal wells.

Propagating hydraulic fractures change the local stress field. This affects the trajectory of nearby fractures propagating simultaneously (e.g. in a multi-cluster stage) or sequentially (e.g. subsequent stages in the same or other laterals), and can induce fracture complexity even in a very simple stress regime with no pre-existing natural fractures.

The geometry of a natural fracture system can dominate the shape of the fracture network developed during hydraulic fracturing.

It is essential to simulate fracture propagation in three dimensions to capture these effects accurately.

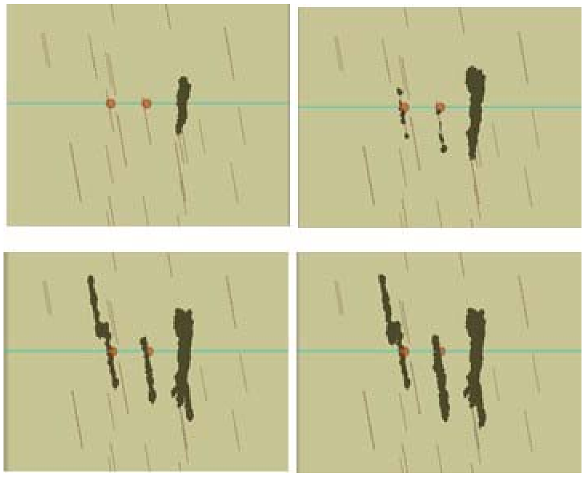

Fig. 8 Map view of fracturing into the DFN.

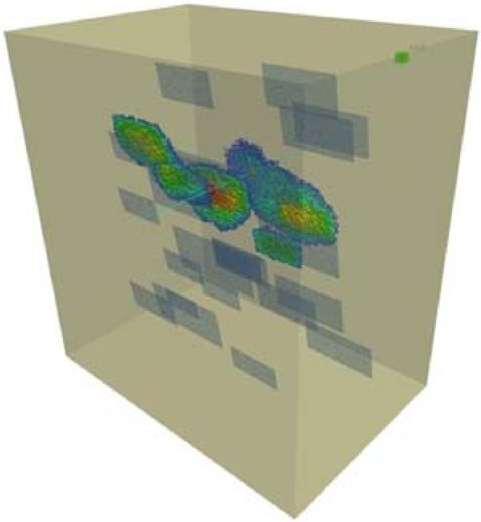

Fig. 9 Perspective view of fracturing into the DFN.

## REFERENCES

1. Damjanac, B. and P. Cundall, 2016, Application of Distinct Element Methods to Simulation of Hydraulic Fracturing in Naturally Fractured Reservoirs, Computers and Geotechnics, 71, 283-294.
2. Mack, M.G., and F. Zhang, 2016, Microseismic Geomechanics for Refracturing ARMA 16-546 presented at the 50th U.S. Rock Mechanics Symposium, Houston.
3. Maxwell, S.C., B.T. Lee, and M.G. Mack, Calibrated Microseismic Geomechanical Modeling of a Horn River Basin Hydraulic Fracture, ARMA 16-0626 presented at the 50th U.S. Rock Mechanics Symposium, Houston.
4. Leonard, P.A., R. Hull, M. Friedrich, S.C.Maxwell, M.G. Mack, D.R. Chorney and F. Zhang, 2016, Geomechanical Modeling of Wolfcamp Completions, presented at URTEC 2016, San Antonio.
5. Olson, J.E., 2008, Multi-fracture propagation modeling: Applications to hydraulic fracturing in shales and tight gas sands, ARMA-08-327 presented at the 42nd U.S. Rock Mechanics Symposium, San Francisco.
6. Cipolla, C.L., X. Weng, M.G. Mack, U. Ganguly, H. Gu, O. Kresse and C.E. Cohen, 2011, Integrating Microseismic Mapping and Complex Fracture Modeling to Characterize Hydraulic Fracture Complexity, SPE 140185 presented at the SPE Hydraulic Fracturing Technology Conference, 24-26 January, The Woodlands, Texas, USA.
7. Damjanac, B., C. Detournay and P.A. Cundall, 2015, Application of particle and lattice codes to simulation of hydraulic fracturing, Comp. Part. Mech. DOI 10.1007/s40571-015-0085-0
8. Lee, B., M.G. Mack and S. C. Maxwell, 2016, Completion Optimization Using a Microseismically Calibrated Geomechanical Hydraulic Fracturing Simulation in a Naturally Fractured Formation, ARMA 16-535 presented at the 50th U.S. Rock Mechanics Symposium, Houston.
9. Chorney, D.R, S.C. Maxwell and M. G. Mack, Hydraulic Fracture Sensitivity Study with a Fully-Coupled Microseismic Geomechanics Model. ARMA 16-625 presented at the 50th U.S. Rock Mechanics Symposium, Houston.
10. Bunger, A.P., R.G. Jeffrey, J. Kear, X. Zhang and M. Morgan, Experimental Investigation of the Interaction among Closely Spaced Hydraulic Fractures. ARMA 11-318 presented at the 45th U.S. Rock Mechanics Symposium, San Francisco.