Hydraulic fracture multi-cluster simulation using *FLAC3D*

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1 INTRODUCTION

Hydraulic fracturing in unconventional reservoirs is a complex process in which stress perturbations are induced. There are many variables that can result in high impact along the borehole completion including stress anisotropy, complex stimulation operations (zipper frac, modified zipper frac), well spacing, stage and cluster spacing. Also, the existence of discrete formations (e.g., with natural fractures, pre-existing joints, local faults) can make the situation worse. Complex stress shadows are induced resulting in irregular fracture geometry as well as Stimulated Rock Volume (SRV) geometry. Even though the completion integrity is designed with higher strength capacity and a safe margin, in some critical cases casing deformation can be affected by the hydraulic fracture operations. It is crucial to get a better understanding of the complex formation stresses to develop and apply mitigation strategies to avoid casing damage and maintain an integer well during the lifetime of the field. Many techniques to model and study the stress shadow effect have been presented by van der Baan, Chorney, and Roche (2016), Nagel, Zhang, Sanchez-Nagel, Lee, and Agharazi (2013), Harper (2016), Zhou and Guo (2012) or Lian, Yu, Lin, and Guo (2015). They differ in numerical modeling approach and assumptions made compared to the content of this paper.

In this paper a method using *FLAC3D* to simulate hydraulic fracture propagation in multi-clusters on a near well model is presented. This approach does not limit the fracture development to a specified fracture plane. The basic concept is to have a ready to use mesh and be able to perform parametric studies on stress and strain induced by reservoir stimulation within a reasonable timeframe. Since the experience shows that the value of numerical modeling studies is often neglected due to relative slow response times compared to e.g. micro seismic measurements and interpretation.

The aim of the modeling is to evaluate the influence of completion stage design on potential well failure due to hydraulic fracture stimulation.

2 MODEL SETUP AND ANALYSIS

The 3D geomechanical model was setup using the finite difference modeling code *FLAC3D* (Itasca Consulting Group, 2012) as seen in Figure 1. A near well model is considered for a sample reservoir with two layers, where the hydrocarbon bearing one is the stiffer and less permeable layer shown in blue. Perforations are placed below the softer caprock with lower porosity, but higher permeability. The mesh was assembled with a volume that covers 600 m by 700 m by 600 m in x, y, and z directions. A total number of 1.8 million elements were defined with higher resolution mesh nearby the wellbore and clusters section. The smallest volume cell is 3.8m3. The model is aligned with the regional maximum horizontal stress orientation. Before starting the stimulation simulation, a mechanical equilibrium was run. *FLAC3D* intrinsic hydraulic-mechanical (HM) coupling was used.

The constitutive material model used is Mohr-Coulomb. Fracture propagation is not limited to a single planar plane away from the perforations. The main driver for propagating the fracture is tensile failure. Once a cell fails in tension, the stiffness of the failed element is reduced and the permeability of the fractur element is increased. The ratio of the permeability increase depends on field response and is a parameter that can be used for model calibration. Fluid leak-off is included in the fluid flow model by activating the fluid modulus in FLAC 3D. Fluid flow is coupled with geomechanical model during the simulation. The fluid leakoff from fracture element to the matrix formation is controlled by the net pressure and formation permeability. A simplification is made for the fluid properties; reservoir and stimulation fluid have the same properties that are equal to the density and viscosity of water at reservoir temperature.
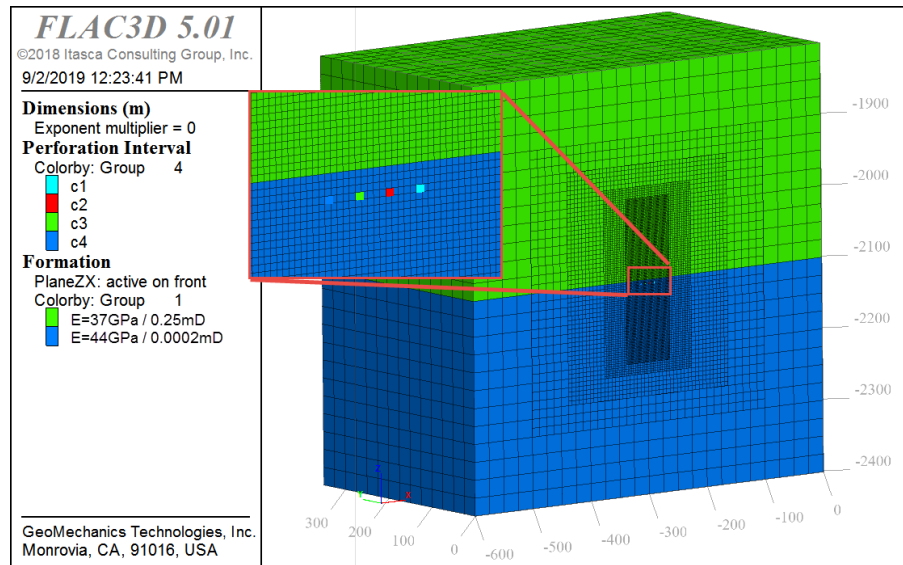

Figure 1. Cross section through mesh with zoom to injection points.

One stage with four clusters was modeled for a period of 100 min. Pumped volume was distributed with the aim to keep the pressure at the location of the perforations of each cluster similar.

The focus of the study is the stress reorientation around the fractures. Detailed modeling of proppant transport is therefore neglected. Nevertheless, routines are implemented to estimate the fracture width based on the volumetric strain induced in the fractured cells.

The study also evaluates induced stresses and strains along the trajectory of the stimulation well. Sensitivity is performed regarding the in situ stress regime, the azimuth of the well in relation to the direction of the principal stresses, and the spacing between the clusters.

The induced stresses and strains are useful in further comparison with failure envelopes of completion designs of the field of interest.

3 RESULTS AND DISCUSSION

The observation from simulation results show that initially the propagation of the fractures stay within a planar plane. Then gradually we see stress shadowing effect starts to constrain the fracture propagation at some locations, resulting in shorter and/or curving fracture planes. In some areas channels interconnecting the main fracture planes are also observed.

Fracture geometry of four clusters is shown in Figure 2. After 100 min of stimulation the outer fractures reached a half-length of about 100 m, while the inner fractures are hindered in their development and only grow in one direction (each in a different one) and up to 50 m half length. The fracture height is smaller for the outer fractures (about 70m) compared to the inner fractures reaching about double the fracture height (140 m). Cross sections along the fracture development plane are show in Figure 3.
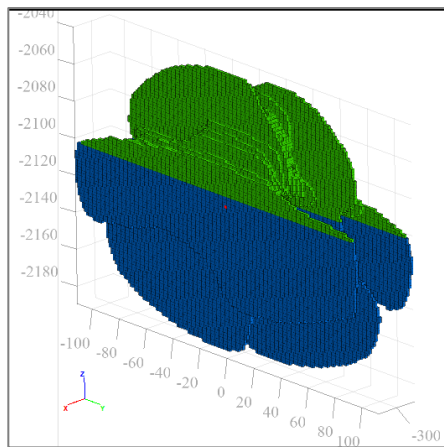
Figure 2. 3D view of fracture development after 100 min of stimulation, units in meter.
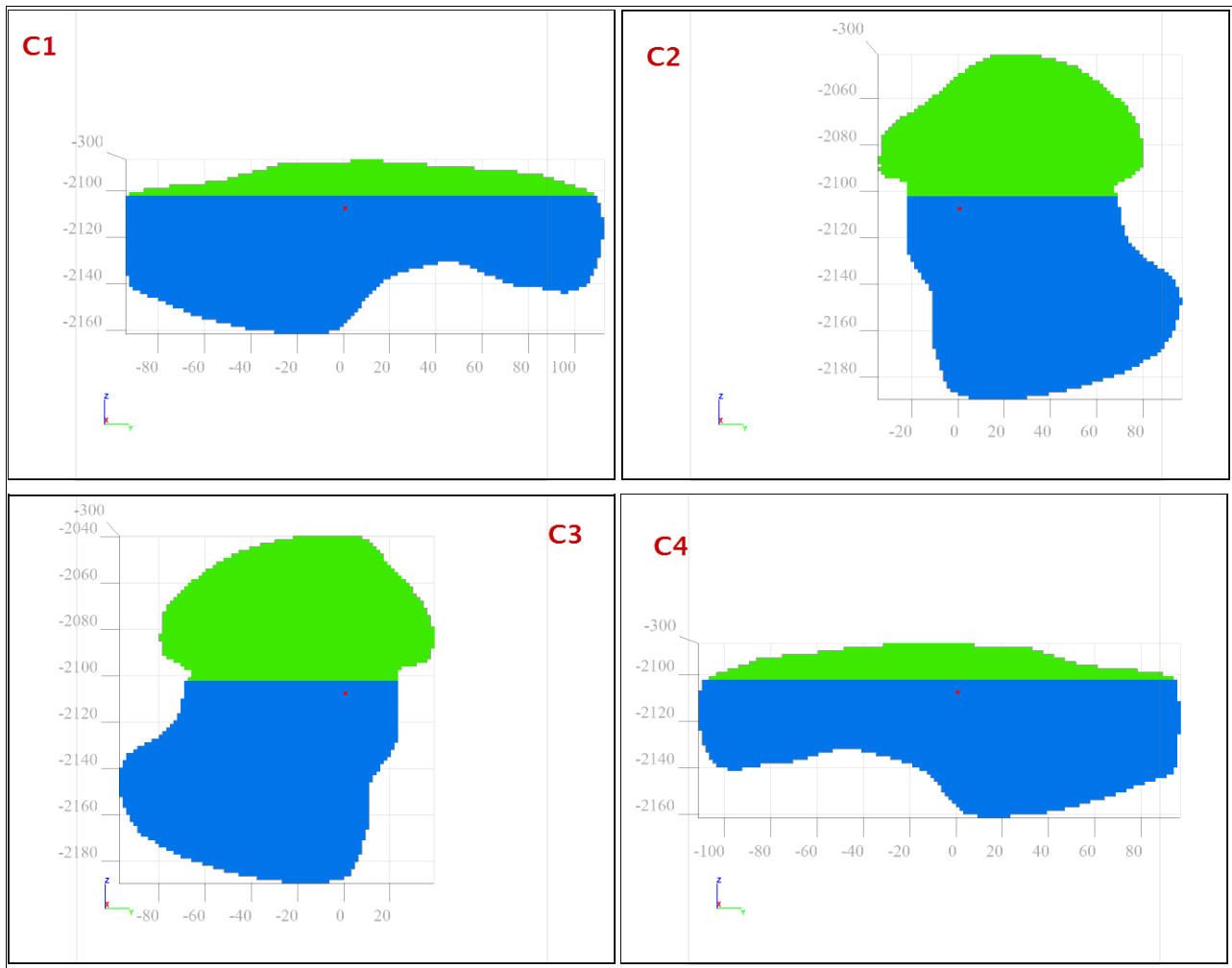

Figure 3. Fracture development after 100 min of stimulation, units in meter. Cross section view of clusters.

The induced strain in the reservoir is extrapolated for different well trajectories at the end of simulation and converted to strain in a coordinate system along the well trajectory. Figure 4 compares the results for fractures developing 90 deg orientation in respect to the well bore path with the fractures developing at 60 deg orientation. Such difference in orientation of the fracture plane to the well path can develop due to local stress reorientation, e.g. caused by natural faults in the reservoir. Axial strain reached 0.2 % at the

edge clusters and is slightly lower for the inner clusters for the 90 deg fracture. Note that positive strain stands for tension along the wellbore (seen in the area of the clusters) and negative strain means compression. For the 60 deg fracture the axial strain reduces to below 0.15%. Evaluating the strain induced perpendicular to the well path we see opposite behavior. The induced strain for the 90 deg fracture stays below 0.02% while the induced strain for the 60 deg fracture goes up to 0.06% and is mainly under tension in the vicinity of the stage (up to 70 m away from the stage center).

Based on experience, the well casing is likely to fail when the strain typically exceeds 3 % - refer also to Bruno (1992) and Bruno (2001). The result from such simulations can provide informative insight on potential well failure due to hydraulic fracture operations. For more practical casing damage risk analysis, a 3D near wellbore geomechanical model with detailed well completion components should be developed and applied to evaluate the casing deformation caused by different loading conditions.
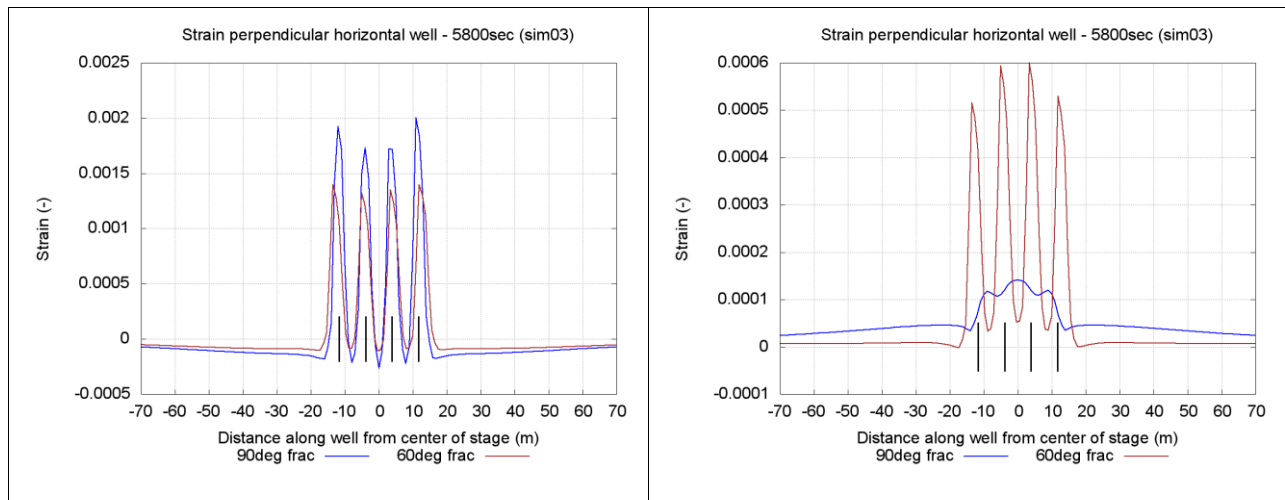

Figure 4. Strain in the reservoir along the well trajectory after 100 min of stimulation. Axial (left) and perpendicular (right) to the wellbore path. Vertical black lines indicate perforation positions.

4 CONCLUSIONS

A 3D geomechanical model to simulate hydraulic fracture propagation in multi-cluster has been developed using *FLAC3D*. A reasonable fracture geometry at each cluster can be predicted from one simulation. Stress shadowing effect causing constraint of fracture propagation in some clusters can be observed in the simulation results. Sensitivity analysis regarding rock mechanical properties, in situ stress conditions and orientation of the well in relation to the in situ stresses can be performed within a week on a reasonably powerful PC.

The influences of local stress reorientation on the induced strains on casing/wellbore were studied. Up to 6 times higher lateral induced strains onto the wellbore are observed if the fracture does develop at an angle of 60 deg in respect to the wellbore path. Induced fractures perpendicular to the wellbore show higher tension induced along the wellbore axis.

Qualitative comparison of induced strains provides a good guideline for optimum stage design at the same time with optimum well design in a given geological setting. Though the model setup provides a flexible application for different fields and sensitivity studies, the computation time still needs improvement for commercial application in operational settings.

Improvements to the approach include: studying the mesh size effect (though the mesh is already refined in the area that will fracture potentially, no sensitivity has been performed on the results if the mesh is further refined).

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