Finite element modelling of fault stress triggering due to hydraulic fracturing

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Summary

In this study we aim to model fault slip due to stress perturbation by hydraulic fracturing. For this purpose, the finite-element modelling package ABAQUS is used with two distinct models. Prior to computing fault slip, ABAQUS first adjusts and equilibrates the stresses. In the presence of faults, ABAQUS attempts to achieve an equilibrium state in several distinct ways: stress adjustment and reaction forces. Here, the reaction-force approach is used. The initial vertical stress is computed based on the overlying rockmass, and the initial horizontal stress is computed subject to the condition that the critical fault stability (CFS) is set to 5 MPa. The stress perturbation by a tensile crack is calculated based on theory by a simple model for crack-tip stress. The combination of both background and crack stress is used as an initial condition for the model to investigate slip. The result is 2.8m of maximum slip along the fault in presence of perturbation due to hydraulic fracturing. This amount of slip along the fault is equivalent to a magnitude 5.6 earthquake, based on fundamental physics of earthquake. Further work is required to better characterize the fault slip. For example, use of a finer computational mesh may result in less distortion of elements and a more accurate result.

Introduction

In 1962, the US military injected waste fluid into a 3971m deep borehole at the Rocky Mountain Arsenal, Colorado (Hsieh & Bredehoeft, 1986). This project triggered earthquakes up to M 5.3 and since that time it has been realized that earthquakes can be induced by fluid injection. Injection of fluid can perturb the stress field and generate new fractures, as well as induce slip on pre-existing faults. Unlike the Arsenal earthquakes, the majority of induced seismicity data show a small magnitude of M ~ 1 (Suckale, 2010). Other examples include Eola Field, Oklahoma with the largest magnitude of M 2.8 (Holland, 2011) or Horn River, Canada with the largest magnitude of M 3.8 (BC Oil and Gas Commission, 2012). These examples the likelihood of damage arising from induced seismicity by hydraulic fracturing is low but it cannot be ruled out. Hydraulic fracturing is being increasingly used for unconventional reservoir development around the globe. This proliferation of use has led to increased public concern about the potential for triggering earthquakes. With this motivation, the objective of the present study is to investigate slip on fault due to stress perturbation by a hydraulic fracture.

Theory

According to Harris (1998), we can define the fault stability by using the Coulomb Failure Stress (CFS). This is difference between the shear stress and the friction force on a fault:

$$
\begin{aligned}
CFS &= \tau - \tau' \\
CFS &= \tau - (\mu(\sigma_n - P)),
\end{aligned}
\tag{1}
$$

which τ is the shear stress on fault, μ is the coefficient of friction, σ_n is the normal stress on fault and P is the pore pressure. Negative CFS value indicates stable condition whereas a positive value implies unstable conditions necessary for slip to occur. The vertical background stress (S_V) is the pressure by the rocks lying above a particular depth. It is described by Twiss and Moores (2007) as:

$$S_V = \int \rho_{layer} g_{layer} dz - P_f \tag{2}$$

Which ρ_{layer} is the density, g_{layer} is the gravitational acceleration and P_f is the effect of fluid-filled pore spaces in rock. The maximum horizontal stress is calculated according to (Steffen et al., 2014):

$$S_H = \frac{S_V[\mu - \mu cos2\theta + |sin2\theta|] + 2CFS - 2\mu P}{-[\mu cos2\theta + \mu - |sin2\theta|]}, \tag{3}$$

which the angle θ is also related to the fault angle by the following relation:

$$\theta = 90 - \alpha. \tag{4}$$

According to Lawn (1975), the stress field by a tensile fracture described by:

$$
\begin{aligned}
\sigma_{11} &= \frac{K_I}{\sqrt{2\pi r}} cos(\theta/2)[1 - sin(\theta/2)sin(3\theta/2)] \\
\sigma_{33} &= \frac{K_I}{\sqrt{2\pi r}} cos(\theta/2)[1 + sin(\theta/2)sin(3\theta/2)] \\
\sigma_{13} &= \frac{K_I}{\sqrt{2\pi r}} cos(\theta/2)sin(\theta/2)cos(3\theta/2) \\
\sigma_{22} &= \nu(\sigma_{11} + \sigma_{33}) \\
\sigma_{12} &= \sigma_{32} = 0,
\end{aligned}
\tag{5}
$$

which θ and r are the angle and radial distance from the tip of the crack. The K term is the stress intensity factor which in an infinite plane with uniform stress σ and crack length 2a is:

$$K = \sigma\sqrt{\pi a}. \tag{6}$$

Example

A Cartesian 2D model is developed for this preliminary study. It includes 3 different parts: a 3 km deep sedimentary basin, upper crust and lower crust. Altogether the model has vertical and lateral extent of 40km and 100km, respectively. A 2 km fault with 45 degree dip angle exists in upper crust. The coefficient of friction on the fault set to 0.6 (Wu and Hasegawa, 1996), which is assumed for an optimally oriented fault. Sides of the model are constrained to move only in the vertical direction, while the bottom of the model does not move and top of model has all degrees of freedom. A tensile crack is located at 2.5 km depth with 100 m length horizontally, above the fault. Young's modulus, Poisson's ratio and density of each layer are shown in figure 1.

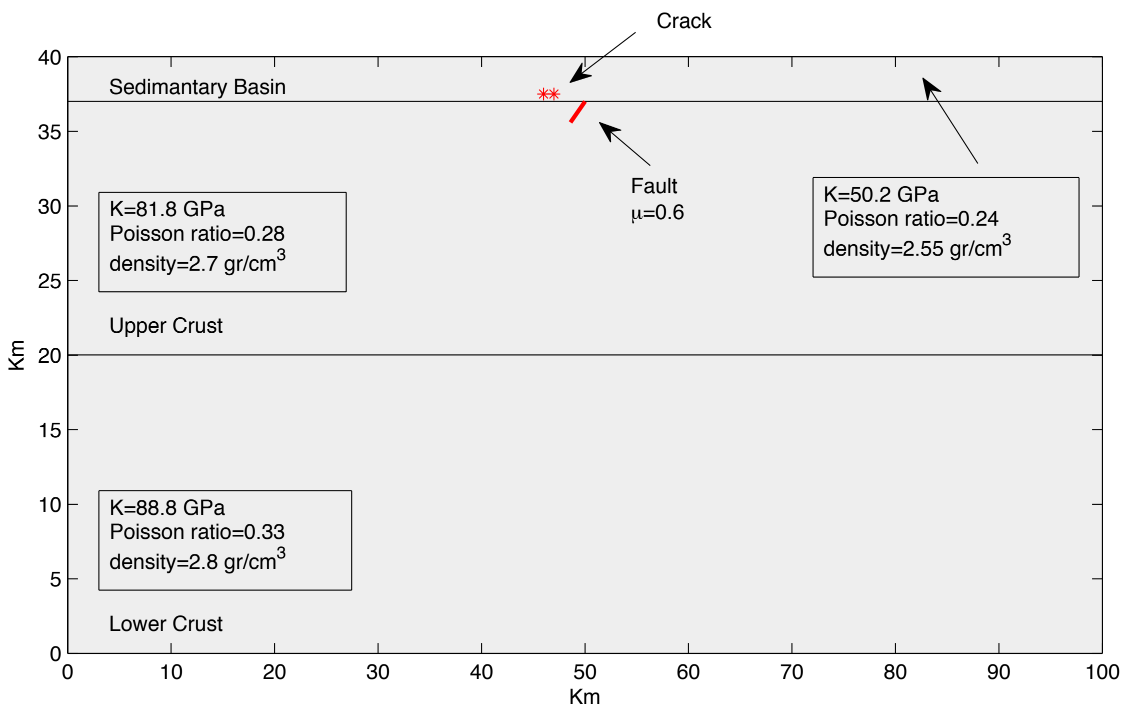

Figure 1: The model which is implemented in ABAQUS, showing 3 layers of 40 km crust. Fault is 2 km long with the 45 degree dipping angle.

As we are interested to investigate fault slip due to stress perturbation by the hydraulic fracture, two models are developed. ABAQUS is not able to give us the fault slip by the initial condition, because by design it first adjusts and equilibrates the stresses. In order to do that, two program options exist. First option is to tie the fault in the model, not to let it slip, and let ABAQUS adjust the stresses. The second option is to use reaction forces. For this purpose we have to fix all the nodes in the model and let ABAQUS adjust the stresses. When, all the nodes are fixed, ABAQUS will generate reaction forces at each node to reach equilibrium. We choose the second approach, because the first one will change the initial stress condition and also will generate deformation within the model. We calculate the average vertical and horizontal background stress in each element. The average stress perturbation due to crack is added to each element. In our modeling we used quadrilateral plane strain elements with 4 nodes (ABAQUS keyword: CPE4). Then we tie the fault which means that the nodes at both sides of the fault do not have relative displacement. Next we fix all the nodes and give this initial stress condition to ABAQUS. At this point all the reaction forces are generated. In the next step we give ABAQUS all the previous stresses as well as reaction forces which was developed through the first step. Reaction forces are loaded on each node at this point. The fault is then opened, and ABAQUS is used to solve for displacement.

Figure 2 shows that when an additional stress perturbation due to hydraulic fracturing is included, the maximum slip on the fault is about 2.8 m. The moment magnitude of earthquake is calculated according to the following equation (Hanks & Kanamori, 1979). A square rupture area is also assumed.

$$M = \frac{2}{3} log M_0 - 10.7 \qquad (7)$$
$$M_0 = \mu AS,$$

which μ is the rigidity of the rock (~30 GPa), A is the rupture area and S is the amount of slip on the fault. Therefore, This 2.8 m of slip along the fault is equivalent to a magnitude 5.6 earthquake.

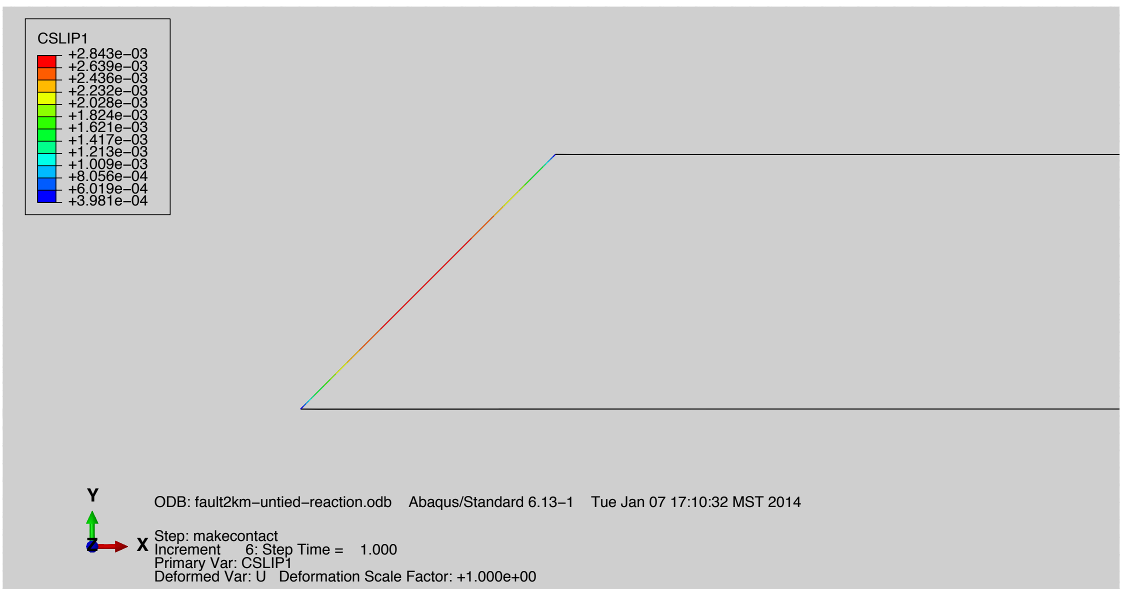

Figure 2: 2.8 m of maximum displacement on fault with perturbation due to hydraulic fracturing. The scale of displacement is km.

Conclusion

In this preliminary study we investigate the effect of perturbation of stress due to hydraulic fracturing on displacement along a fault. In order to do that we use two separate steps of calculations. In the first step, the initial stresses including vertical and horizontal stress and the perturbation due to hydraulic fracture are applied. At this point all the nodes are fixed which yields the creation of reaction forces to satisfy the equilibrium condition. Through the second step, fault is open and ABAQUS solve the model to reach the equilibrium state. The fault has the maximum displacement of 2.8 m which is equivalent to a magnitude 5.6 earthquake. Further work is required to better characterize the fault slip. For example, use of a finer computational mesh may result in less distortion of elements and a more accurate result. In the future, parameter sensitivity (e.g. fault dimensions, position of tensile crack relative to fault, friction parameters on fault surface) has to be evaluated.

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