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# Geomechanical Modeling of Induced Seismicity Associated with Triggered Fault Slip during Multi-Stage Hydraulic Fracturing

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## Summary

The link between fluid injection and induced seismicity is studied through the geomechanical modeling of a mutli-phase hydraulic fracturing treatment in the proxmity of a fault. Synthetic seismicity is used to quantify seismic energy released by the slippage on the fault for different injection scenarios. Moment release rate typically drops during the shut-in period, but depending on the distance between the fault and the injection point, a delay can be seen between the start of the injection and the increase of slip on the fault, thus acceleration of moment release rate can be observed during shut-in periods. Stress shadowing also has an influence on the moment release rate. This basic model could be used as a framework to examine the impact of other geomechanical characteristics or other operational factors to help mitigate seismicity when faults begin to be active.

## Introduction

Concerns about triggered seismicity from fault reactivation due to injection activities have risen in the last few years. Suspect seismic events greater than magnitude 4 are being reported in British Columbia and Alberta that are thought to be linked to hydraulic fracturing. However the link between fault reactivation and fluid injection is still not well understood and requires quantification through proper geomechanical and hydraulic investigations.

We use a fully hydraulically-mechanical coupled, 3-D model (Damjanac and Cundall, 2014) to simulate fault reactivation during a hydraulic fracturing treatment. Synthetic seismicity is an output of the model and can be used to study the spatio-temporal evolution of seismic deformation linked to fault reactivation. Synthetic microseismicity can help quantify the amount of seismic energy released by the slippage on the fault for different injection scenarios. The model shown in this paper is based on a case study in the Horn River Basin by Snelling et al. (2013).

## Geomechanical models

The model consists of five planar hydraulic fractures oriented along the maximum horizontal stress and a fault about 300 m long oriented at a 45° angle from the hydraulic planes (Figure 1). Each hydraulic plane represents one stage of a hydraulic fracturing treatment. In this scenario, we have used a simple representation of each hydraulic fracture stage as a single, planar fracture without the interaction of other pre-existing fractures (e.g. Zhang et al., 2015). The first stage is the closest to the fault plane while the last stage is the furthest away. Spacing between stages is 30 m. The surrounding stress field is strike-slip and the difference between minimum and maximum horizontal stresses is assumed to be 20 MPa.

The injection is confined in the Horn River formation. The injection rate is 19.2 $m^3$/min per stage. Fluid is injected for an hour and a 30 minute shutin period is considered between two stages. Two simulations are run: model 1 has five stages whereas model 2 was intended to simulate an operational changes and has only three stages(equivalent to increasing the stage spacing to 60 m).

Synthetic seismicity is based on amount of incrimental, episodic slip on the fault plane. The magnitude is obtained using Hanks and Kanamori’s (1979) relation between moment and magnitude.

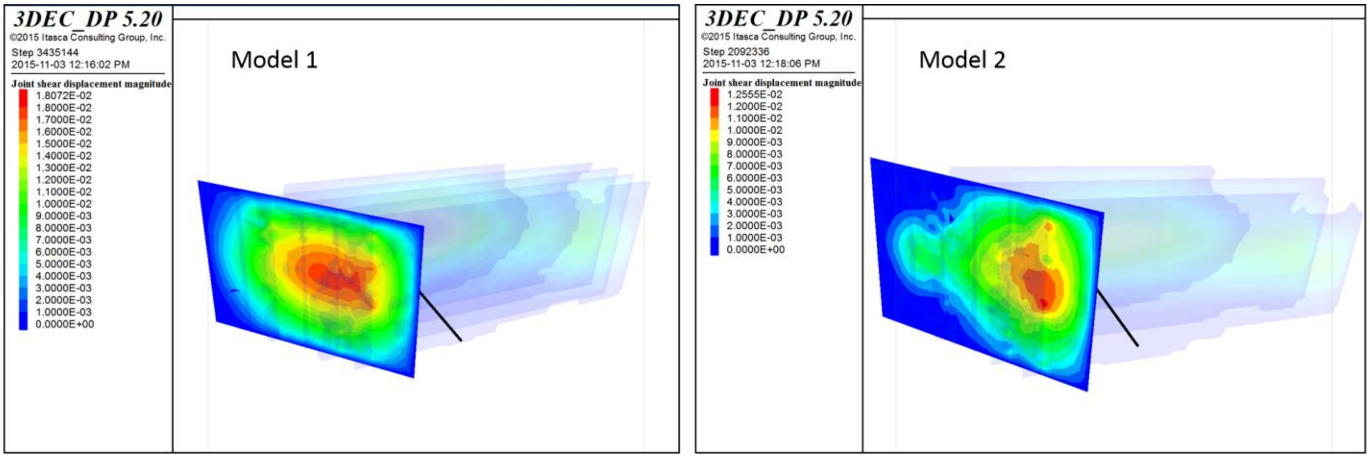


*Figure 1. Shear displacement on the fault for both models. The black line defines the wellbore. Aperture of the hydraulic fracture planes is shown in transparency.*

## Results

Figure 1 shows the shear displacement on the fault plane for both simulations. When model 1 is considered (left of Figure 1), slip accumulates over the majority of the fault plane. If stages are skipped or stage spacing increased (right of Figure 1), less shear displacement is found and is significantly reduced towards the end stage which is the further away from the fault plane. This can also be seen from the corresponding microseismic events shown in Figure 2. There are less events for model 2 and they are thinning out towards the last stage.

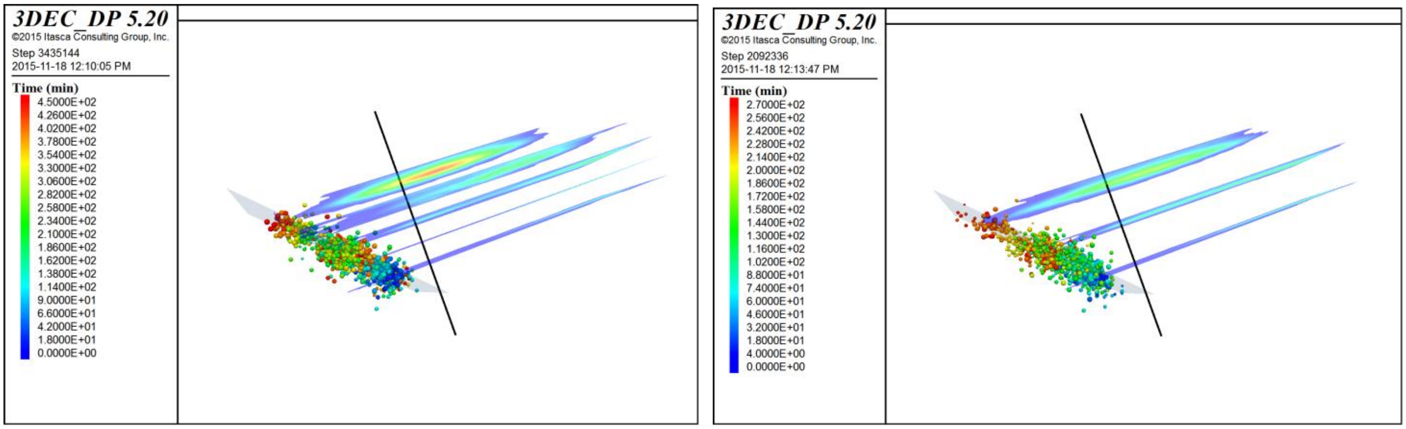


*Figure 2. Synthetic microseismic events color-coded according to time for both simulations, 5 stages on the left and 3 stages on the right. Aperture of the hydraulic fracture planes is shown in transparency*

Figure 3 shows the temporal evolution the cumulative seismic moment for both models. During some stages (e.g. the first stage), the moment release rate increases during the injection as the hydraulic fracture grows into the fault, and facilitates slip by decreasing the effective clamping force. However, fracturing during stages 3 and 4 in model 1 and stage 2 in model 2 don't seem to accelerate the seismic moment release. This is likely due to stress shadowing between the neighboring stages, which pushes the fluid in the other direction away from the fault (see aperture on hydraulic fracture planes in Figure 1 and 2). This effect is also visible on the temporal magnitude distribution in Figure 3. Actual magnitude values are decreasing over the period corresponding to these particular stages. It is also interesting to note the seismicity during the shut-in periods. After the first stage the moment release rate drops at the end of pumping, however around 350 minutes of model 1, the moment increases during a shut in period. This effect of fault activation after pumping has been observed before, and here is attributed to continued flow after pumping stops.

After the first stage in both models, a delay can be osberved between the start of the injection and an increase in seismic moment. Injection points at the later stages are further away from the fault plane. It thus takes more time for the fluid to flow close enough to the fault plane to pressurize it and induce slippage.

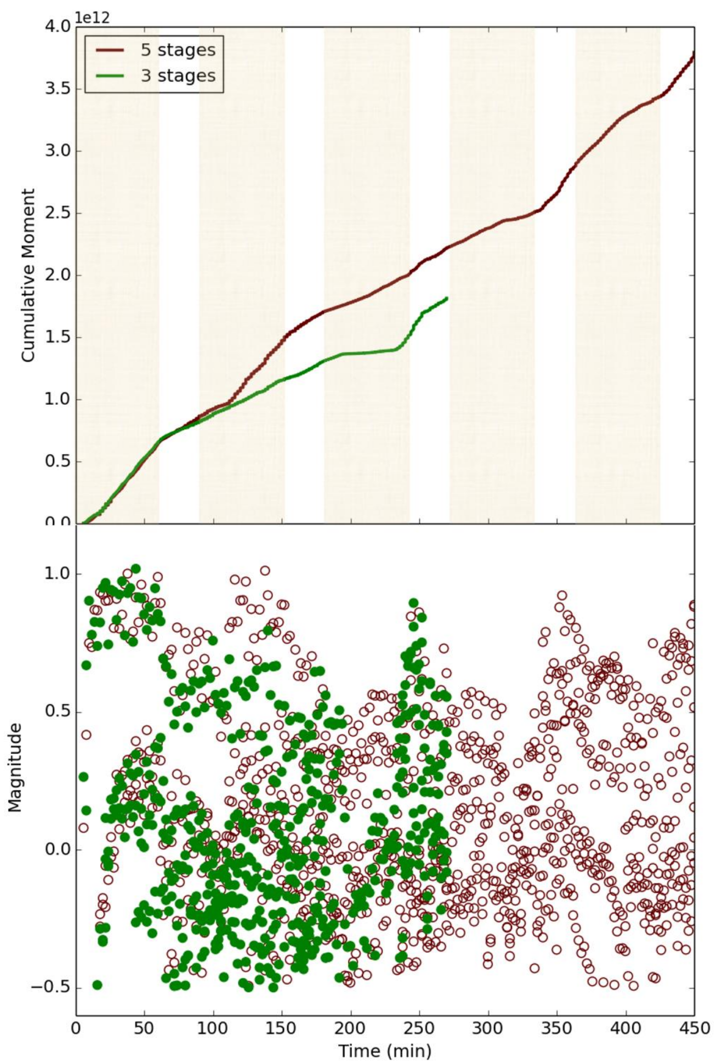


*Figure 3. Cumulative moment (top) and magnitude (bottom) evolution with time for both models (model 1 in red and model 2 in green). The yellow shaded areas represent the injection periods. Events of magnitdue below -0.5 are not displayed for clarity.*

## Conclusions

Simulations of fault reactivation linked to hydraulic fracturing are studied including a quantification of the total seismic moment release. The relatively simple model is able to reproduce seismic deformation characteristics observed in field data. Results show that even stages distant from the fault have an influence on the slippage on the fault. The effect is delayed when the injection point is further away from the fault but still exists. Stress shadowing from neighboring stages helps reduce the fault activity by pushing the fluid in the opposite direction, thus decrease the pressure on the fault. Simple models such as described here can be used to history match scenarios when induced seismicity occurs and explore various potential operational change scenarios. In this example, we reduced the number of stages and found that the number of largest seismic events reduced. Other scenarios could also be considered of reducing rate, volume or skipping additional stages to mitigate additional seismicity as required in the AER subsurface order 2015-007. The basic model could also be used as a framework to examine the impact of other geomechanical characteristics (e.g. stress state, fault properties including orientation, friction and hydraulic characteristics) or other operational factors (multiple clusters, longer shutin periods, fracture flowback etc). Such an investigation could help establish best practices to mitigate seismicity when faults begin to be active. Finally, the model points to the benefit of enhanced sensitivity to detect the small magnitude background events for sufficient sampling of the moment release rate. If only larger magnitude seismicity is detected, there is less information to understand the context of the fault deformation to operation.

## Acknowledgements

### References

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