The effect of permeability loss on induced seismicity during depletion-induced reservoir compaction

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Introduction

In the last few years, earthquakes which have been attributed to produced water re-injection have been felt at the surface in, for example, the continental United States and have received lots of attention. However, earthquakes have also been seen to be induced by fluid production (Segall 1989). The cause of these earthquakes is thought to be total stress changes which are induced by fluid production (Segall 1989).

In the fully coupled theory of poroelasticity, the gradient of pore pressure acts as an internal force to produce deformation and stress changes in the rock (Chang and Segall, 2017). Thus, the larger the pore pressure gradient (drawdown of reservoir pressure) required to produce a certain amount of fluid, or the smaller the productivity index, the larger the resulting stress changes will be. During reservoir depletion, compaction can result in permeability losses (Schutjens et al., 2004). Lower permeability results in higher pore pressure gradients being required to produce fluid. For this reason, the effect of permeability loss during depletion-induced compaction on induced seismicity is investigated.

Methodology

A two phase FVM (finite volume method) flow model based on the continuity equation for mass balance has been developed. This model accounts for compaction-induced permeability loss by assuming a linear relationship between permeability loss and mean effective stress assumed to be valid over the range of effective mean stress considered and based on Schutjens et al., 2004. This permeability model is valid for the near-elastic range as defined by Schutjens et al., 2004. Generally, permeability changes outside of the near-elastic range can be much more drastic (Boutéca et al., 2000). The flow model was constrained to remain in the near-elastic range at all times. The model was sequentially coupled to a plane strain FEM (finite element method) mechanical model based on the conservation of momentum with no external forces. Based on the linear theory of poroelasticity, pressure and stress changes were predicted resulting from reservoir depletion via a horizontal well. These pressure and stress changes were then used to calculate the changes in Coulomb stress for an optimally oriented fault according to Andersonian faulting theory (Anderson 1951). This ultimately allowed for the calculation of the seismicity rate, which is described as the rate of seismic events compared to background levels following Dietereich 1994, and extended by Segall and Lu, 2015.

Numerical experiments were performed both with and without the compaction-induced permeability loss for all three standard stress regimes. In this way, the seismicity rate for all cases could be readily compared.

Results

The total-stress changes induced above and below the reservoir are larger in the case that the permeability decreases within the reservoir because of compaction. In the case of a reverse faulting stress regime (and a strike-slip faulting stress regime if the well is drilled parallel to the minimum principal stress), increased stress changes result in an increase in seismicity rate as the largest stress changes occur in the direction horizontally perpendicular to the well. An example of the permeability loss due to compaction and the resulting seismicity rates can be seen in Figure 1 for a reverse faulting stress regime. In effect, the reduced permeability due to compaction had the result of lowering the productivity index, or increasing the pore pressure gradient required to produce an increment of fluid, which in turn resulted in a less compressive state of stress in the reservoir. Consequently, above and below the reservoir, the most likely places for seismicity to occur in this stress regime (Segall 1989), the state of stress was more compressive, increasing the shear stress acting on a potential optimally oriented fault.

Permeability reduction within the reservoir also results in higher (less disturbed) pore pressures and smaller total-stress changes at the margins of the reservoir, the most likely place for induced seismicity in a normal faulting stress regime (Segall 1989). In terms of induced seismicity in a normal faulting stress regime, a higher pore pressure (less stable) and a more compressive horizontal stress (more stable) are have opposing effects for this stress regime and the resulting seismicity rate is only slightly increased in the case that compaction-induced permeability loss is accounted for.

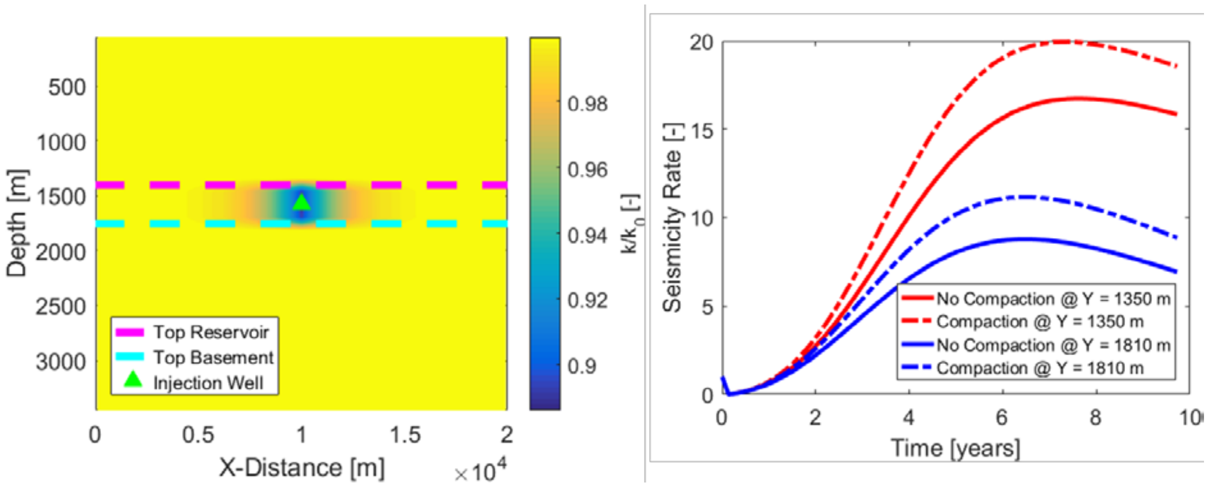

Figure 1: An example result from a reverse faulting stress regime, (a) the permeability loss due to compaction and (b) the resulting seismicity rates when this permeability loss is and is not accounted for. The seismicity rates are taken at various depths (Y) vertically in-line with the producing well. The simulation is plane strain with injection occurring via a horizontal well.

All in all, however, compaction-induced permeability loss has the effect of increasing the likelihood of induced seismicity in all cases despite the fact that the permeability loss was limited (in the near-elastic range as defined by Schutjens et al., 2004) when compared to the sometimes order of magnitude decreases that can be seen during inelastic changes (Zhu and Wong 1997).

Conclusion

Compaction-induced permeability loss has the effect of increasing the induced total-stress changes that result from fluid production. Increased stress changes result in larger predicted seismicity rates that occur at the margins and outside of the reservoir. These results therefore have reservoir management implications for fluid-producing reservoirs (such as not producing at rates that require too large a pressure drawdown), especially when considering the enhanced permeability loss that can occur outside of the elastic effects considered here (Boutéca et al., 2000).

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References

Anderson E. (1951) *The Dynamics of Faulting and Dyke Formation with Applications to Britain*. Edinburgh, Oliver and Boyd

Boutéca M., Sarda J., Vincké O. (2000) Consitutive law for permeability evolution of sandstones during depletion. 2000 SPE International Symposium on Formation Damage Control. Doi: 10.2118/58717-MS

Chang K., Segall P. (2017) Reduction of injection-induced pore-pressure and stress in basement rocks due to basal sealing layers. Pure and Applied Geophysics 174:2649-2661. Doi:10.1007/s00024-017-1567-1

Dietereich J. (1994) A constitutive law for rate of earthquake production and its application to earthquake clustering. Journal of Geophysical Research 99:2601-2618. Doi:10.1029/93JB02581

Schutjens P., Hanssen T., Hettema M., Merour J., de Bree P., Coremans J., Helliesen G. (2004) Compaction-induced porosity/permeability reduction in sandstone reservoirs: data and model for elasticity-dominated deformation. SPE Reservoir Evaluation & Engineering 7:202-216. Doi:10.2118/88441-PA

Segall P. (1989) Earthquakes triggered by fluid extraction. Geology 17:942-946

Zhu W., Wong T. (1997) The transition from brittle faulting to cataclastic flow: Permeability evolution. Journal of Geophysical Research 102:3027-3041. Doi: 10.1029/96JB03282