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Probabilistic maximum magnitude estimation of induced earthquakes from stochastic modelling

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Summary

Current efforts to analyze the risk of induced seismicity caused by fluid injection (e.g. hydraulic fracturing operations, CO2 sequestration, wastewater disposal etc.) and to develop mitigation strategies with a rigorous scientific basis are hindered by a dearth of numerical models incorporating the full physics of the problem. In particular, the complexity of the slip process is ignored, which neglects important details such as whether the induced slip is seismic or aseismic. Such details are of vital importance for maximum expected magnitude estimation and seismic hazard assessment. Our software bridges this critical gap by using a tool to simulate both aseismic and seismic slip due to modelled pore pressure and/or stress changes on pre-existing faults. Magnitudes can then be estimated from the modelled slip. Here we show modelling results for several hydraulic fracturing case studies, comparing modelled maximum magnitudes to observed seismicity. The results show excellent potential for aiding induced seismicity risk assessment and mitigation.

Theory

Anthropogenic fluid injection into the subsurface is known to have the potential to cause induced seismicity (Ellsworth, 2013). Modelling of induced seismicity is complicated by the fact that several models have been proposed to explain the mechanisms of fault activation by hydraulic fracturing (Eyre et al., 2019). The most common is an increase in pore pressure within the fault zone, which leads to a reduction in effective normal stress acting on the fault (Bao and Eaton, 2016). Alternatively, poroelastic coupling between hydraulic fractures and the rock matrix is capable of altering fault-loading conditions without any hydraulic connection (Segall and Lu, 2015). More recent work has shown that aseismic slip may play a major role (Eyre et al., 2019), whereby distal, unstable regions of a fault are progressively loaded by aseismic slip on proximal, stable regions of the fault that are stimulated by pore pressure and/or stress changes due to fluid injection. A full simulation of seismic and aseismic slip is therefore necessary to account for this behaviour when modelling induced seismicity to estimate maximum expected magnitudes.

Results, Observations, Conclusions

Our new modelling approach accounts for the three mechanisms above by assessing stress changes due to both pore pressure changes, poroelastic effects and slip-induced stress changes, while also acknowledging that not all slip induced by these changes is likely to result in seismicity. Simulations can be ran a large number of times for input parameters that are assigned stochastically from distributions that can be based on the available knowledge of the area, as many of the parameters are often poorly constrained and models are always a simplification of the true Earth. In this manner, we can estimate the probabilities of generating an event of a certain magnitude based on the modelled injection scenario and parameter distributions.

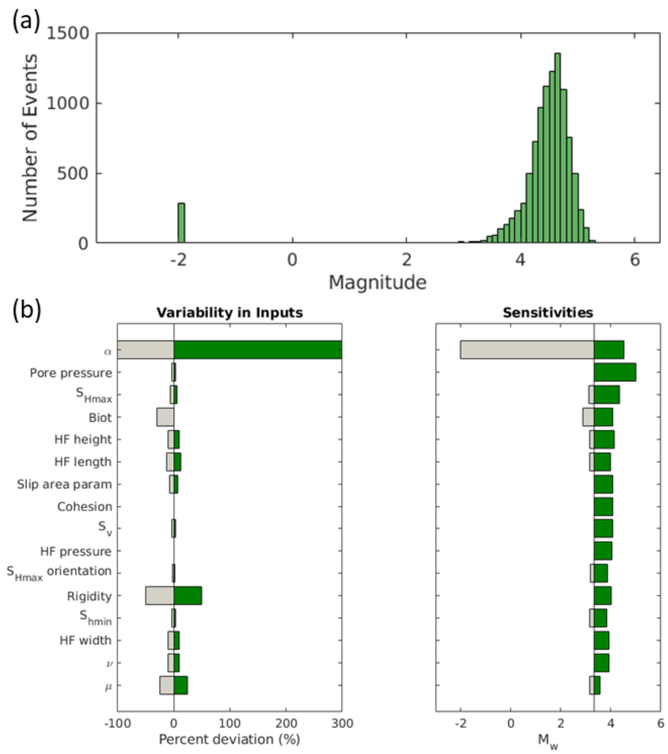

Figure 1. (a) Simulation results for 10,000 iterations. (b) Example of the input parameter distributions and sensitivities of the results shown as tornado plots.

The modelling is being tested for various case studies from the Western Canadian Sedimentary Basin and a number of other basins worldwide. An example of the results for 10,000 iterations is shown in Figure 1, for a case study detailed in Eyre et al. (2019a, 2019b) that resulted in a magnitude 4.1 earthquake. The mean magnitude of 4.3 and median magnitude of 4.5 from the simulations are reasonable estimates of the true maximum magnitude in the case study. Probabilities for events exceeding assigned maximum magnitude thresholds can also be estimated from the resulting distributions. In this example, results suggest a high probability of events of M > 3.0 (97%), which is unsurprising given the proximity of two large fault segments to multiple injection stages and their favorable orientation to slip. The modelling suggests a low (< 4%) probability of generating a M > 5.0, which is an important hazard consideration. Sensitivity analysis to many of the input parameters is also shown in Figure 1b, which can be very useful for designing mitigation strategies. The modelling results and comparison with the case study suggest that our method has good potential for successfully modelling fluid injection scenarios and producing realistic induced seismic events and associated magnitudes. It therefore has promise for evaluating site-specific injection scenarios prior to operations for induced seismicity risk management and mitigation.

We are developing this modelling into a user-friendly software package. Ultimately, our work aims to significantly reduce the financial, environmental and social risk of induced seismicity, as well as the potential to cause damage to local populations and infrastructure.

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References

Bao, X., and D. W. Eaton, 2016, Fault activation by hydraulic fracturing in western Canada: Science, **354**, 1406–1409.

Ellsworth, W. L., 2013, Injection-Induced Earthquakes: Science, **341**, 1–8.

Eyre, T. S., D. W. Eaton, D. I. Garagash, M. Zecevic, M. Venieri, R. Weir, and D. C. Lawton, 2019a, The role of aseismic slip in hydraulic fracturing - induced seismicity: Science Advances, **5**, eaav7172.

Eyre, T. S., D. W. Eaton, M. Zecevic, D. D'Amico, and D. Kolos, 2019b, Microseismicity reveals fault activation before Mw 4.1 hydraulic-fracturing induced earthquake: Geophysical Journal International, 218, 534–546.

Segall, P., and S. Lu, 2015, Injection-induced seismicity : Poroelastic and earthquake nucleation effects: Journal of Geophysical Research : Solid Earth, **120**, 5082–5103.