ESC2016-266, 2016
35th General Assembly of the European Seismological Commission

Numerical modeling of seismicity induced by large-scale CO_2 injection in a multilayered sedimentary system

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Overpressure caused by the direct injection of CO_2 into a deep sedimentary system may produce changes in the state of stress, as well as, have an impact on the sealing capabilities of the targeted system. The importance of geomechanics including the potential for reactivating faults associated with large-scale geologic carbon sequestration operations has recently become more widely recognized. In this context, here we review and summarize some recent modeling efforts, aimed at understanding the possible seismicity induced by CO_2 storage and its relation to potential leakage to shallow groundwater aquifer during active injection. The simulations were conducted using TOUGH-FLAC, a simulator for coupled multiphase flow and geomechanical modeling. We carried out both quasi-static and dynamic simulations, with an explicit representation of a fault. In the case of quasi-static modeling, a strain softening Mohr-Coulomb model was used to model a slip-weakening fault slip behavior, enabling modeling of sudden slip that was interpreted as a seismic event, with a moment magnitude evaluated using formulas from seismology. In the case of dynamic modeling, we simulate the fault behavior as strain-softening or rate-dependent, analyzing the frequency behavior at surface and the possible effects of friction properties on slip.

This work aims at studying the fault responses during carbon dioxide injection, focusing on the short-term (5 years) integrity of the storage repository, and hence, on the potential leakage towards shallow groundwater aquifers. We account for stress/strain-dependent permeability and study both the fault reactivation and the leakage through the fault zone. We analyze several scenarios related to the injected amount of CO_2 (and hence related to potential overpressure) involving both minor and major faults, and study induced seismicity and leakage for different stress/strain permeability coupling functions, as well as increasing the complexity of the system in terms of hydromechanical heterogeneities. Our analysis shows that induced seismicity associated with fault reactivation may not necessarily open up a new flow path for leakage. Results show a poor correlation between magnitude and amount of fluid leakage, meaning that a single event is generally not enough to substantially change the permeability along the entire fault length. Furthermore, results show that a thin caprock or aquifer induces smaller events, but a much higher leakage to the upper aquifer. The amount of leakage is reduced drastically by assuming a multi-caprock, multi-aquifer system.

Results of dynamic modeling show how the nucleation of fault rupture takes place at the bottom of the injection reservoir. The analysis of the frequency spectrum shows that the seismicity induced by CO_2 injection may produce low damage to ground surface structures and cause nuisance to the exposed population, in the worst-case scenario, and at earthquake epicenter. The analysis of friction behavior shows that a velocity-weakening produces larger ruptures and generates larger magnitude seismic events. Heterogeneous faults have been considered including velocity-weakening or velocity strengthening sections inside and below the aquifer, while upper sections being velocity-neutral. Nucleation of rupture in a velocity strengthening section results in a limited rupture extension, both in terms of maximum slip and rupture length. For a heterogeneous fault with nucleation in a velocity-weakening section, the rupture may propagate into the overlying velocity-neutral section in cases in which the velocity weakening and associated friction drop is large enough.

Finally, we compared the previous 2D modeling approach with a more complete 3D formulation. Results show that a well-scaled 2D model satisfactorily reproduces the 3D modeling results. However, the 3D model permits extending the analysis to other factors (e.g., injection well direction).