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Effect of non-linear fluid pressure diffusion on modeling induced seismicity during reservoir stimulation

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Success of future enhanced geothermal systems relies on an appropriate pre-estimate of seismic risk associated with fluid injection at high pressure. A forward-model based on a semi-stochastic approach was created, which is able to compute synthetic earthquake catalogues. It proved to be able to reproduce characteristics of the seismic cloud detected during the geothermal project in Basel (Switzerland), such as radial dependence of stress drop and b-values as well as higher probability of large magnitude earthquakes (M>3) after shut-in. The modeling strategy relies on a simplistic fluid pressure model used to trigger failure points (so-called seeds) that are randomly distributed around an injection well. The seed points are assigned principal stress magnitudes drawn from Gaussian distributions representative of the ambient stress field. Once the effective stress state at a seed point meets a pre-defined Mohr-Coulomb failure criterion due to a fluid pressure increase a seismic event is induced. We assume a negative linear relationship between b-values and differential stress. Thus, for each event a magnitude can be drawn from a Gutenberg-Richter distribution with a b-value corresponding to differential stress at failure. The result is a seismic cloud evolving in time and space. Triggering of seismic events depends on appropriately calculating the transient fluid pressure field. Hence an effective continuum reservoir model able to reasonably reproduce the hydraulic behavior of the reservoir during stimulation is required. While analytical solutions for pressure diffusion are computationally efficient, they rely on linear pressure diffusion with constant hydraulic parameters, and only consider well head pressure while neglecting fluid injection rate. They cannot be considered appropriate in a stimulation experiment where permeability irreversibly increases by orders of magnitude during injection. We here suggest a numerical continuum model of non-linear pressure diffusion. Permeability increases both reversibly and, if a certain pressure threshold is reached, irreversibly in the form of a smoothed step-function. The models are able to reproduce realistic well head pressure magnitudes for injection rates common during reservoir stimulation. We connect this numerical model with the semi-stochastic seismicity model, and demonstrate the role of non-linear pressure diffusion on earthquakes probability estimates. We further use the model to explore various injection histories to assess the dependence of seismicity on injection strategy. It allows to qualitatively explore the probability of larger magnitude earthquakes (M>3) for different injection volumes, injection times, as well as injection build-up and shut-in strategies.