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Simulation of the inelastic deformations of porous reservoirs under cyclic loading relevant for underground hydrogen storage

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Subsurface geological formations can be utilized to safely store large-scale (TWh) renewable energy in the form of green gases such as hydrogen. Successful implementation of this technology involves estimating feasible storage sites, including rigorous mechanical safety analyses. Geological formations are often highly heterogeneous and entail complex nonlinear inelastic rock deformation physics when utilized for cyclic energy storage. One of the major concerns of energy storage in the subsurface is the consequent ground surface subsidence or uplift. Several researchers in the past have reported subsidence in the carboniferous sandstone fields across the world which are used to produce hydrocarbons (Hettema et al., 2002; Teatini et al., 2011). When these reservoirs are used to store hydrogen, this results in seasonal cyclic loading on the reservoir that could cause permanent subsidence or uplift depending on the operating conditions and the rock characteristics. This calls for accurate modeling of subsidence for understanding the grain scale physics of the rocks in the subsurface. In this work, we present a novel scalable computational framework to analyze the impact of nonlinear deformation of porous reservoirs under cyclic loading. The proposed methodology includes three different time-dependent nonlinear constitutive models to appropriately describe the behavior of sandstone, shale rock and salt rock. Inelastic deformations such as plasticity observed in sandstone (Pijnenburg et al., 2019), viscoplasticity observed in shale (Haghighat et al., 2020) and creep in rock-salt (Spiers et al., 1990) are commonly observed in underground formations by these rocks.

To model creep, a power law formulation, where strain rate is a function of stress, was employed for brittle rocks (Bérest et al., 2019; Xu et al., 2012). To model plasticity of sandstone, cyclic modified cam clay model (MCC) (Carter et al., 1979) is further extended to account for viscoplasticity of shale rocks using a Perzyna based formulation (Haghighat et al., 2020). An implicit time-integration scheme is developed to preserve the stability of the simulation. Firstly, these models are implemented and compared with the existing literature. In order to ensure its scalability, the numerical strategy adopts a multiscale finite element (Ramesh Kumar & Hajibeygi, 2021) formulation, in which coarse scale systems with locally-computed basis functions are constructed and solved. Further, the effect of heterogeneity on the results and estimation of deformation is analyzed. Lastly, the Bergermeer test case –an active Dutch natural gas storage field comprising predominantly of sandstone– is studied to investigate the influence of inelastic deformation on the uplift caused by cyclic injection and production of gas. The constitutive laws are calibrated based on the uplift recorded by GPS stations for 1.75 years and then the uplift is compared with the GPS recorded stations for the remaining 2 years. The present study shows acceptable subsidence predictions in this field-scale test, once the properties of the finite element representative elementary volumes (REV) are tuned with the experimental data.

Participation

In-Person

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