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Effect of loading rate on mechanical behavior and deformation mechanisms in clay-bearing sandstones

Takahiro Shinohara, Christopher Spiers, and Suzanne Hangx
Utrecht University, Department of Earth Sciences, Faculty of Geosciences, Utrecht, Netherlands (t.shinohara@uu.nl)

Fluid extraction from subsurface reservoir sandstones frequently results in surface subsidence and induced seismicity, as observed in the Groningen Gas field (Netherlands). The cause lies in reservoir compaction driven by pressure depletion and the associated increase in effective overburden stress. Compaction in sandstones often includes elastic and significant inelastic components. The inelastic part is at least partly due to rate- or time-dependent processes, such as intergranular sliding or stress corrosion cracking. However, few mechanism-based rate/time-dependent compaction laws exist, despite the need to evaluate the impact of reservoir exploitation on field time scales (1-100 years). To help bridge this gap, we systematically investigated the effect of loading strain rate in the range from 10^{-3} to 10^{-9} s^{-1} in a series of triaxial compression experiments performed on water-saturated Bleurswiller sandstone samples with porosities of 21.07±0.15 % and composed of 66 % quartz, 28 % feldspar and 4 % clay. This material was chosen because of similarity to the Groningen sandstone but greater uniformity. We explored conditions of confining pressure (39 MPa), pore pressure (10 MPa) and temperature (100 °C) corresponding to in-situ values for Groningen. Axial strains up to 3 % were imposed. Our results showed combined elastic plus strain hardening (inelastic) loading behavior, up to a peak stress reached at 0.8-1.0 % strain, followed by strain softening towards a steady residual stress attained at 1.5-2.0 % strain. A systematic lowering of stress-strain curve levels was observed with decreasing strain rate, such that peak and residual stresses decreased respectively from 88 and 74 MPa at 10^{-3} s^{-1} to 70 and 61 at 10^{-9} s^{-1}. No effect of loading rate is observed at differential stresses below ~ 50% of peak stress. At higher differential stresses up to peak, net sample stiffness (stress-strain curve slope) decreases with decreasing strain rate. Using the curve obtained at 10^{-3} s^{-1} as a reference, we determined the excess strains measured at rates of 10^{-4} to 10^{-9} s^{-1} at fixed differential stresses up to the peak. By extrapolating this empirical relation to field strain rates associated with gas production in Groningen (i.e. 10^{-12} s^{-1}), it is estimated that ~30 % more compaction strain is developed under field conditions, at current differential stresses in the field (i.e. ~ 60 % peak stress), than in laboratory experiments at rates of 10^{-3} to 10^{-5} s-1. Additional experiments at varying temperature and confining pressure show sensitivities that suggest that the observed effect of strain rate is likely associated with a combination of time-dependent grain failure by stress corrosion and intergranular sliding. Work is in progress to assess the effect of varying mineralogy by conducting similar experiments on clay-free, quartz-rich Bentheimer sandstone. Our results show that time-dependent inelastic deformation plays an important role in estimating reservoir deformation and associated change in stress associated with fluid production

from sandstone reservoirs, like the Groningen reservoir. Such effects could lead to underestimation of surface subsidence and induced seismicity, if not adequately accounted for. The present experiments thus provide important data for testing current models for rate-dependent reservoir compaction.