A kinematic model for observed surface subsidence above a salt cavern gas storage site in Northern Germany

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In nation-wide radar satellite time series data of Germany, a linear subsidence motion of several kilometer spatial wavelength shows up south-east of Kiel, northern Germany. The center region of this signal, showing line-of-sight displacement velocities of about 2 mm/a, coincides with the facilities of a gas storage site managing two in-service and one out-of-service caverns in the salt dome beneath. The three caverns have been water-drilled only a few hundred meters apart in 1971, 1996 and 2014 into a large halite salt dome, which has risen up there to depths of around 1000 m. Their sizes range within a couple of 100.000 m³. Above the salt body thick deposits of mainly chalk, silk and claystone below layers of clays, silts, sands and glacial marls in the upper 200 m form a relatively strong roof layer.

We hypothesize that despite a thick and competent cover layer, the long-term ductile behavior of halite, which evidently causes shrinking of the cavern volumes through time, results in the observed continuous surface subsidence across several square kilometers. We present an attempt to test the hypothesis by optimizing a simple kinematic model to fit the surface subsidence signal. Using equivalent body forces to represent an isotropic volume point source embedded in a viscoelastic host medium below a horizontally layered elastic roof medium, we estimate the horizontal position of a single cavern, its depth and the corresponding volume change at the cavern. The medium properties at the cavern sites are well known from borehole geophysical analyses, but likely vary strongly laterally. We use InSAR time series data from two ascending look directions and two descending.

Our results show that a cavern at about 1200 m depth and in very close proximity to above-ground facilities of the storage site can indeed be associated with the observed ground motion. The best-fit models pin the location to the known positions, also in depth. The estimated volume loss is slightly larger than 20.000 m³ per year and is in the same order of volume loss estimated from volume measurements inside the actual caverns.

The model approach we present, a single kinematic point source for three caverns and a one-dimensional medium model, is simple, the signal-to-noise ratio of the satellite data is rather small and furthermore there are considerable spatial gaps in the InSAR time series data in areas of agriculture and forests. However, with a computationally fast forward calculation of surface displacements we can afford to propagate data error statistics that account for spatially correlated errors to model parameter uncertainty estimates in a Bayesian way through model ensembles. We
plan to add modeling errors of the medium to better grasp their potential influence on the volume loss estimations. The optimization code we use, Grond, is part of the seismological open-source software toolbox Pyrocko (pyrocko.org). The data is openly available at bodenbewegungsdienst.bgr.de.