Recent Developments in Hydrogeologic Applications for Strain Tensor Analyses

Larry Murdoch, Scott DeWolf, Rob Moak, Leonid Germanovich, Austin Smith-Jones, Soheil Roudini

Changes in fluid pressure deform porous media and this effect occurs in a variety of hydrogeologic processes, from the change in storage during pumping or injection to fluctuations in water levels caused by barometric pressure. We have developed instruments for measuring small strains in porous media, and we have used the resulting strain data to evaluate well testing, hydraulic fracturing, manual loading at the ground surface, and ambient hydrologic processes, like rainfall and evaporation. A particularly important application is the use of strain tensor data measured at shallow depths to analyze well tests or hydraulic fractures conducted at much greater depths. An early demonstration of this technique was conducted at the North Avant Field north of Tulsa, Oklahoma, where Pennsylvanian sandstone creates a confined aquifer and oil reservoir at a depth of 530m. We have showed that the strains caused by injecting into the aquifer could be measured at a depth of 30m and used to evaluate the properties of the aquifer.

We recently expanded the array of strainmeters at the North Avant Field by deploying three more instruments at shallow depth (30m) along with a deep instrument at 520m depth in the winter, 2021. The deep instrument is deployed in shale caprock slightly above the aquifer. To our knowledge, the deep strainmeter at the North Avant Field is the deepest strainmeter ever deployed and this required refining methods originally developed for shallow deployments. The instrument was lowered to depth on oil field tubing and cemented in place using techniques and materials developed for use in oil wells. Optical fiber used to communicate with the instrument was cemented in the annulus on the outside of tubing. This is significant because the techniques we used could readily be extended to greater depth, suggesting that strainmeters can be deployed over a wide range of depths for monitoring critical subsurface processes. For example, it suggests that strainmeters could be deployed through the caprock to monitor for leaks from underlying CO_2 storage reservoirs.

The strainmeter array at the North Avant Field has been used to characterize deformation during a series of injection tests in the spring and summer, 2021. All the new strainmeters respond to pumping, and the strainmeters we installed earlier also responded. To our knowledge, this is the first application of well testing in a deep aquifer that was monitored by an array of strainmeters—our earlier work used strainmeters at a single location. We are currently analyzing the strain data using an analytical solution, a proxy-based Bayesian inversion algorithm, and other methods.

Strainmeter data has also been used to characterize periodic pumping tests by us and Riley Blais. A periodically varying pumping rate causes both hydraulic head and strain signals that vary with the same period as the pumping. The peaks and troughs of the head in monitoring wells lag behind the peaks and troughs of the head in the pumping well, and this lag time increases with distance from the pumping well. The lag time of the pressure and the distance to the monitoring well can be used in a simple analysis to estimate the hydraulic diffusivity of the aquifer. The lag time determined from strain data can be used to estimate aquifer properties using the same analysis that works for the pressure only for strain data measured at particular locations. That is because the strain field in a confining unit advances upward, laterally and then downward even though the pressure in the underlying aquifer only advances laterally, according to our recent simulations. We have field data showing that a small periodic signal superimposed on an injection rate at the North Avant Field will create a periodic strain signal at shallow strainmeters. The field data and the recent simulations suggest that including a periodic component to injection or pumping and then monitoring the resulting strain signal could be a way to monitor the subsurface.