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Surface Deformation for Monitoring Subsurface Pore Pressure in CCUS Operations: A Case Study from the West Hastings EOR Field

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Summary

Monitoring subsurface pressure evolution is fundamental to the safety of Carbon Capture, Utilization, and Storage (CCUS) projects. The injection of CO2 into geological reservoirs alters pore pressures, generating stress fields that manifest as measurable deformation at the surface. Because uncontrolled stress buildup can lead to geomechanical hazards and societal concern, effective surveillance strategies are required to validate storage integrity. This study evaluates the utility of surface deformation as a non-invasive proxy for tracking these subsurface pressure variations.

The research focuses on the West Hastings oil field in Texas, USA, discovered in 1934 that had reached a state of significant depletion by the late 20th century. In 2010, the field was revitalized by Denbury Inc. through a large-scale CO2-Enhanced Oil Recovery (EOR) project, transforming the site into an ideal natural laboratory for monitoring pressure evolution during active repressurization. Time-series deformation derived from Interferometric Synthetic Aperture Radar (InSAR) and Global Navigation Satellite System (GNSS) observations is integrated with injection rate data within a poroelastic modeling framework. By calibrating the model against observed surface displacements - incorporating both horizontal and vertical components - reservoir pressure changes are successfully estimated. The results presented include findings from both simulated predictions and observations collected from operational sites, assessing the effectiveness of current monitoring strategies. This approach proposes a future pathway toward a comprehensive Monitoring, Measurement, and Verification (MMV) methodology using geodetic observations.

Theory / Method / Workflow

Injecting or withdrawing fluid from a reservoir leads to changes in fluid pressure within the subsurface, which in turn induces surface strain and deformation in the surrounding strata. Theoretically, with knowledge of the geomechanical properties of the caprock, it is possible to invert the underground stress distribution and quantify the spatial and temporal migration of injected fluids. Space geodetic techniques have previously been utilized to investigate various types of surface deformation related to underground fluid movement, including subsidence due to groundwater withdrawal (Amelung et al., 1999), and earthquakes induced by massive wastewater injection (Keranen et al., 2014). Building on these foundations, this study focuses on employing space geodetic techniques to constrain the location and migration of injected CO2.

Sentinel-1A and Sentinel-1B TOPS-mode synthetic aperture radar (SAR) data were processed using the ISCE-2 and MintPy software packages, following a standardized small-baseline subset (SBAS) workflow optimized for long temporal baselines and millimetric accuracy (Berardino et al., 2002; Rosen et al., 2012; Zhang et al., 2019). The processing aimed to recover a temporally consistent deformation time series for the West Hastings EOR field that could be compared directly with GNSS observations and used as input to the poroelastic modeling framework. The interferometric phase was unwrapped using the Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping SNAPHU (Chen & Zebker, 2001). Topographic phase removal employed the Shuttle Radar Topography Mission (SRTM) 1-arcsecond digital elevation model (Farr et al., 2007). Atmospheric artifacts were then corrected using Generic Atmospheric Correction Online Service (GACOS) zenith total delay (ZTD) products (Yu et al., 2018)

To anchor the InSAR results with high-precision point data and address the challenge of detecting small deformation rates, continuous GNSS measurements were utilized from stations DEN1 and DEN2 within the injection block A (Figure 1). Deformation at these stations was derived relative to a reference station, DEN4, located in East Hastings. DEN4 was selected as the stable reference frame because it is situated outside the active injection zone. The raw GNSS time series were detrended to remove the regional subsidence signal caused by groundwater extraction (aquifer depletion) that affects the broader Gulf Coast region (Wang et al., 2024), ensuring the remaining signal reflected only the poroelastic response. This integration of GNSS provides essential constraints using horizontal components, which are crucial for inverting underground plume migration and enhancing the accuracy of ground deformation measurements.

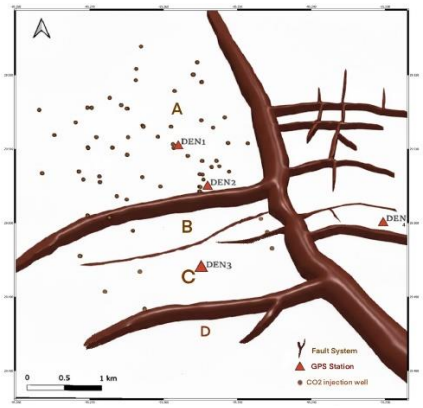


Figure 1 Spatial distribution of the permanent GNSS stations across the Hastings Field.

A semi-analytical poroelastic model (POEL) was employed to simulate the surface deformation field (Wang & Kümpel, 2003), driven by production and extraction rates derived from Railroad Commission of Texas (RRC) datasets (Figure 2). A key aspect of this workflow was the simultaneous incorporation of both horizontal and vertical displacement components into the inversion process. To account for the structural complexity of the reservoir, the "image method" was utilized (Silverii et al., 2021) to model bounding faults as reflective boundaries. This allows for the validation of InSAR observations against semi-analytical models that consider the actual injection rates and geomechanical conditions of the site.

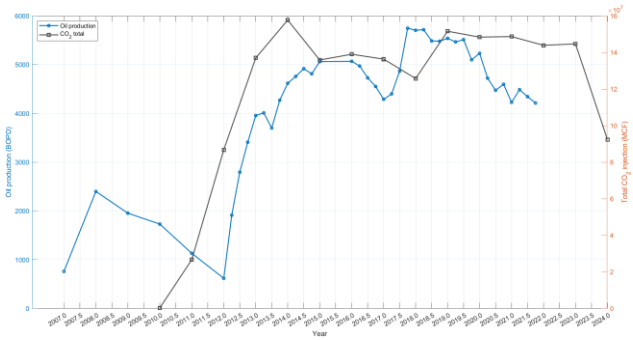


Figure 2 production and extraction rates derived from Railroad Commission of Texas (RRC) datasets

Results, Observations, Conclusions

The results indicate a high degree of consistency between the modeled and observed deformation patterns (Figure 3). The InSAR-derived Line-of-Sight (LOS) displacement shows a strong correlation with the projected GNSS observations at stations DEN1 and DEN2, validating the remote sensing workflow. The POEL model successfully replicated the spatiotemporal evolution of the surface deformation; by incorporating both horizontal and vertical components, the model provided a tight fit to the observed geodetic data. Most significantly, the surface-calibrated model yielded subsurface pore pressure estimates that closely matched the expected pressure evolution derived from injection records. This confirms that the surface deformation field is a direct and reliable reflection of reservoir mechanics.

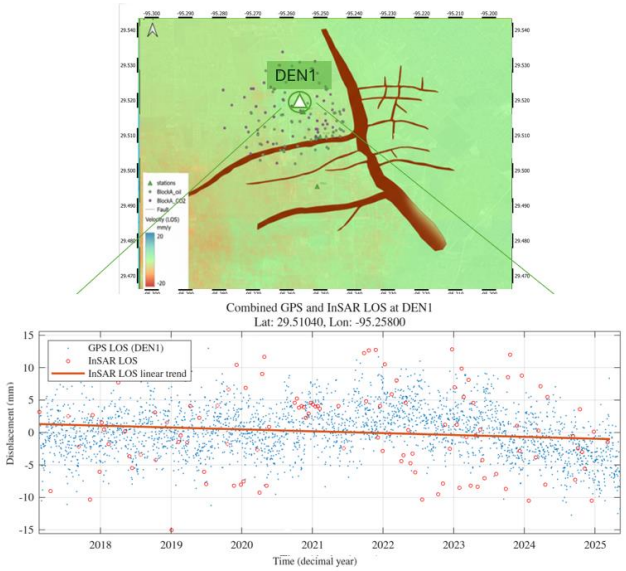


Figure 3 Comparisons of Interferometric Synthetic Aperture Radar (InSAR) line-of-sight (LOS) time series with Global Navigation Satellite System (GNSS) time series projected into the LOS

Novel/Additive Information

The primary contribution of this study is the demonstration that a simplified analytical model, when properly adjusted for boundary conditions and constrained by multi-component surface deformation, can yield high-fidelity pressure estimates without the need for complex numerical simulations. By rigorously combining the vertical and horizontal displacement components the volumetric source mechanism is resolved with high precision. This integration allows the inverted subsurface pore pressure to match the actual bottom-hole pressure reported at the wells in the field. Consequently, this research establishes that surface-based geodetic monitoring can provide results comparable to direct downhole measurements, offering a scalable and cost-effective methodology for reservoir surveillance.

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