A Summary Review Based on Case Studies of the Challenges Related to the Comparison of Displacements Measured by PS-InSAR and Simulated by Geomechanical Coupled to Groundwater Models

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Land subsidence is currently a great challenge for regions densely populated lying over compressible sediments. Mexico City (Ortega-Guerrero et al., 1999; Ortiz-Zamora et al., 2010), Hanoi (Nguyen et al., 2022), Huwei (Tsai et al., 2018 ; Chu et al., 2021), Houston (Kearns et al., 2015 ; Area et al., 2012 ; Miller et al., 2019), Tehran (Mahmoudpour et al., 2016), Las Vegas (Yan, 2007; Burbey, 2002), CanTho (Van Ty et al., 2021), Florence (Ceccatelli et al., 2021) and Lorca (Fernandez-Merodo et al., 2021) are only a few example of cities with subsidence issues. Exploitation of groundwater is the most cited cause of subsidence. Groundwater production creates a decrease of water pressure in the saturated geological medium and based on the Terzaghi principle, any increase of the effective stress can cause consolidation in a porous medium, in confined as in unconfined conditions (Dassargues 2018).

Interferometric Synthetic Aperture Radar (InSAR) technology is used to map the displacement patterns and quantify surface motion over time. It has been shown that InSAR provides an extremely cost-effective means of measuring ground surface displacement over large areas with a fine spatial resolution and precision within the centimeters under ideal conditions (Peng et al., 2022). Persistent Scatterer InSAR Interferometry (PS-InSAR) (Ferretti et al., 2000; Ferretti et al., 2001; Ferretti et al., 2002; Ferretti et al., 2007) technique is one of the most prevalent InSAR algorithms developped mostly for overcoming the decorrelation. Integration and comparison of PS-InSAR-derived displacement measurements with simulated displacement by geomechanical models coupled to groundwater flow models is broadly used for better understanding of the subsurface consolidation mechanisms. However, the practical implementation of such application still has its own challenges, which has received less attention in the literature. Developments in the use of InSAR results have involved inverse modeling (i.e., with groundwater flow and geomechanical models) providing values for aquifers properties (Chaussard et al. 2014; Gualandi and Liu 2021; Jiang et al. 2018; Miller and Shirzaei 2015; Miller et al. 2017; Motagh et al. 2017).

Using PS-InSAR processing, multiple localized land subsidences have been identified in the Antwerp and Leuven areas. On the right bank of the river Scheldt, within the borders of the city of Antwerp, the harbor of Antwerp was gradually developed leading to dock excavations in the estuary polders environment. PS-InSAR was used to detect, map and study the ground displacements (Declercq et al., 2021). Those parts of the subsurface that were disturbed by human activity are referred as 'anthropogenic layers' and are very compressible. However, other possible consolidation drivers such as consolidation of the most compressible sublayers induced by groundwater drainage and pumping are considered (Choopani et al., 2021).

The city of Leuven lies on a multilayer aquifer system called 'Brulandkrijt', consisting of interbedded chalk and sandy aquifers with clayey aquitards. Two areas of significant subsidence have been detected in the North of Leuven showing possibly a delayed consolidation process of the compressible low permeability aquitards.

Using these two case studies as examples, we show how PS-InSAR-derived subsidence observations can be compared to results of hydrogeological and geomechanical modeling. The general methodological workflow with the different steps of a groundwater model construction is described in detail in Dassargues (2018). In the most common case, which is the simulation of subsidence caused by groundwater withdrawal, the most widely used conceptual approach consists in simulating the groundwater flow problem in fully 3D conditions. The water pressure results from this 3D flow model are then prescribed at each time step in the different nodes of a 1D geomechanical model.

One of the most used software code on a regional scale is MODular groundwater FLOW model (MODFLOW). Many 1D-geomechanical model have been developed to simulate land subsidence caused by groundwater withdrawal. The SUB package, which is developed for simulating regional compaction of semi-permeable layers using MODFLOW is the most used software for land subsidence simulations (Hoffmann et al., 2003; Leake et al., 2007; Kooi et al., 2018; Leake et al., 2010). In the workflow of SUB package in MODFLOW, porous media flow is modeled in 3D, but compaction is simulated as a 1D process. An advantage of the SUB package is that it considers the assumption and the calculation of a delay for propagating water pressure decrease within the compressible beds, that are practically low permeability layers.

The current study is part of a more comprehensive work that focuses on the practical challenges of the comparison of simulated displacement in a fully coupled model to PS-InSAR observations. Following this methodology applied to the case studies of Antwerp and Leuven, the summary of the challenges is as follows.

A possible ‘loss of coherence’ corresponding to changes in physical characteristics (e.g., in vegetated areas) is the basic obstacle for InSAR applications leading us to use multi temporal technique such as PS-InSAR which are offering time series of deformation only at the location of Permanent Scatterers (PS). As a result, the fundamental limitation of PS-InSAR for land subsidence monitoring is that it cannot provide a spatially continuous map of displacements. Additionally, a time lag between radar dataset acquisitions is another constraint that prevents us from fully comparing simulated to observed time series of displacements.

The complexity and spatial variability of the geology and of the different hydrogeological and geotechnical processes that take place simultaneously in the subsoil mean that one measured value of subsidence may correspond to several possible causes. Hydraulic parameter characterization is required for groundwater flow modeling, compressibility values and preconsolidation stresses in all considered layers are required for geomechanical modeling. The assessment of their spatial variability and distribution can be very challenging and depending on the local sedimentological conditions. Parameter values from sample-based boreholes, which are often sparsely distributed, could not be a good representation physical characteristics of the whole unit. The number of observation wells can be limited and not so regularly monitored.

Another conceptual challenge when dealing with most groundwater-geomechanical models is that the elastic and inelastic compressibility coefficients are most often assumed to be constant over the simulation period. This is not the case in the reality as the compressibility is dependent on the preconsolidation stress (i.e., the maximum stress that the layer has endured previously). In unconfined conditions, the effective stress is less increased by pumping or drainage than in confined conditions as the decrease in pore pressure is partially balanced by a decrease in the total stress addition when the water table drops (Dassargues 2018, Guzy and Malinowska, 2020).

Consequently, comparing PS-InSAR-derived displacement measurements to results from groundwater flow coupled to geomechanical models is never a simple process. There is no single model to represent every case of land subsidence. It takes many years and many studies to collect the adequate data to establish a representative coupled model of the surface deformation with an accurate understanding of the occurring processes.

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