There are numerous underground gas storage (UGS) systems in the Northern Italian Po Plain area; they are in depleted gas reservoirs, which were converted into storage units from the 1970s. In this urbanized areas, reliable predictions of ground movement (subsidence/rebound) caused by reservoir compaction/expansion induced by UGS operations are mandatory for ensuring the safety of both storage systems and urban settlements. Forecast analyses are commonly faced via a multi-disciplinary 3D numerical simulation approach. In case of subsidence analysis, the modelling approach is effective if based on a solid knowledge of the deformation behaviour of the soil or rock under changing stress conditions. Mechanical properties, adopted for model characterization, are defined via laboratory analyses, well logs and seismic surveys data interpretation. The model is eventually calibrated based on production data and land surface movement measurements, if available.

The scope of the paper is to expand on the knowledge of the underground deformation behaviour by involving two UGS (named field A and field B) in the Po Plain area, one already object of a publication (Codegone et al., 2016). The subsidence analysis of each case study was developed with a multi-disciplinary 3D numerical simulation approach and mechanical model calibration was 10+ years of InSar data. Based on the subsidence analysis results and the analysis of InSar data, a common correlation between induced pressure variation in each reservoir and corresponding ground movement was inferred, resulting in an analogous deformation behaviour.

**Overview of the case studies**

The Po Plain represents the foredeep-foreland domain of the Northern Apennines whose complex Oligocene-to Neogene evolution resulted in a buried arcuate fold-and-thrust belt (Fig. 1). Compressional tectonics led to the N-ward migration of folds and blind thrusts that progressively incorporated the Po Plain clastic infill and its substratum. The Po Plain present-day subsurface architecture is essentially known through seismic reflection data collected since 1945 for hydrocarbon explorations (Pieri and Groppi, 1981). Fields A and B are sited in the outer and central domains of the Ferrara-Romagna Arc, respectively. Both the traps consist of NW-SE asymmetric anticlines associated to NW-SE striking, NE-verging thrusts. The investigated gas-bearing formations are hosted in the Plio-Pleistocene clastic infill of the eastern Po Plain. This sequence includes Pliocene–early Pleistocene transgressive marine shale (Santerno Fm.) and foredeep turbidites of early-mid Pliocene age (Porto Corsini Fm.) and mid-late Pliocene age (Porto Garibaldi Fm.). In particular, the reservoirs belong to the late Pliocene-early Pleistocene Porto Garibaldi Fm.; the Santerno Fm. provided the reservoir caprocks. The pre-Pliocene substratum includes Mesozoic shelf carbonate, mid Eocene-late Miocene shelf-distal marl, Messinian evaporitic deposits and submarine fan-delta conglomerate. The overlying Quaternary sequence includes slope to deltaic clastic deposits that recorded the Po Plain progradation up to the complete filling of the foreland basin (Ghielmi et al., 2010).

![Figure 1](image)

**Figure 1** A) Simplified structural map of the eastern Po Plain. B) Geological cross section (location in Fig. 1A). Modif. from Pieri and Groppi, 1981; Toscani et al., 2009

The case studies are two independent gas-bearing reservoirs at an average depth of 1200 m ssl and areally spaced of about 50 km. Each reservoir consists of a sand and silty sand formation bounded by lateral aquifer. After two decades of primary production, both reservoirs were converted into UGS systems. They have been operated at a maximum injection pressure close to the discovery pressure value with a summer injection phase and a winter production phase.
Method

A coherent and full dataset is available for each reservoir modelling, including: 2/3D seismic survey, around six decades of production+storage data, well-logs at 60+ and 80+ respectively for case A and case B, petrophysical and fluid properties; in situ microfrac and MDT stress tests, deformation and strength parameters from lab and logs, ground surface movement data. The 3D numerical modeling for each system was developed independently because they are hydraulically separated and the induced ground movement is not superimposed. Furthermore, each single modelling was developed with a high degree of detail without computational time restriction. An extended geological model was set up for each case; it effectively reproduces the main stratigraphic/structural features of the investigation domain for subsidence analysis (i.e. the reservoir itself and its surrounding formation up to the surface). A multiphase flow numerical model (FDM) was set up and calibrated: it provided the forcing function applied to the geomechanical model, i.e. spatial/temporal evolution of pore pressure in the reservoir and surrounded aquifer. Finally, subsidence forecasts were developed via a stress-strain FEM model, set up and characterized by geological/structural features and petrophysical/mechanical properties. The model calibration, based on 10+ years of surface movement data, improved both the geomechanical characterization and the reliability of the model prediction.

Analysis of the ground movement data

Land displacement was provided by satellite images (PSInSARTM) (Castelletto et al. 2010). Because the signal induced by an UGS is easily identifiable due to its cyclical/seasonal frequency, the analysis of InSAR data provides information about both the magnitude and the areal extension of the ground movement ascribed to the UGS and the effects of natural processes and other anthropogenic activities. The ground movements of the control points above each reservoir (Fig. 2) show a seasonal/cyclical trend clearly related to the UGS pore pressure variation: the total vertical amplitude is in the range of [10-20] mm for case A, [15-25] mm for case B. Horizontal displacement are negligible. The vertical displacements of control points outside the area of influence show common amplitude in the range of [2-5] m and a frequency not correlated with, or even opposite to, storage operations. They can be ascribed to natural thermic, meteoric phenomena and water production. Furthermore, in case B, a progressive subsidence (from 10 to 30 mm in 13 years) is shown for the point outside the UGS influence cone: that info was used to depurate the anomalous trend shows by point B3.

![Figure 2 Average reservoir pressure and control points vertical movements, case A (a) and case B (b)](image)

Furthermore, maps of surface vertical movements for each storage cycle were defined (examples in Fig. 3). The information was adopted to constrain the dimension of the numerical aquifer surrounding the reservoir during the dynamic simulation phase: as well known, the subsidence is ascribed to pressure variation induced in the all hydraulically continuum reservoir+aquifer system.
Results and discussion

For both cases, triaxial compression tests were performed on both the cap rock compact clays and the reservoir dense sand, under isotropically consolidated undrained conditions (CIU). The calculated static elastic modulus values under loading condition, $E_I$, are in the order of few GPa for both cases (at confining pressure coherent with the in situ condition). Furthermore, for case A, lab data allowed to determine the unloading/reloading static elastic modulus, $E_{II}$, which results 3 times higher than the $E_I$, coherently with previous publication (Ferronato et al. 2003). $E_I$ represents the deformation behaviour induced by primary production in a virgin, normally consolidated formation; instead $E_{II}$ better describes the deformation of a formation subjected by successive unloading/reloading conditions due to the reservoir refilling phase and storage operations. Furthermore, density and sonic logs at different wellbores were interpreted to calculated the dynamic elastic moduli versus depth: for both cases, the results are quite high (between 6 and 18 GPa) considering the lithologies and the in situ conditions.

Each geomechanical model was calibrated according to the pressure variation simulated by the dynamic calibrated model and the InSar data. For both case studies, calibration process results in deformation parameter values equal to 3 times $E_I$, i.e. equals to $E_{II}$. The good match obtained between measured and simulated data (in terms of relative displacement for each cycle) is presented in Fig. 4.

Finally, Fig. 5 shows the ratio between the ground vertical movement ($\Delta u$) and the pressure variation ($\Delta p$) for each production/injection cycle, for the two cases. The following considerations are derived: 1) each system response in terms of vertical variation is stable in time, for a given $\Delta p$; a sound and stable behaviour could be forecast with high accuracy; 2) the responses of the two systems are comparable and the discrepancies can be ascribed to a superposition of factors, no one predominant. Intrinsic, specific heterogeneities and peculiar small/regional scale geological characteristics are
present in the two investigated volumes. The stiffness of the two reservoirs from the back analysis phase are comparable, unless some GPa. The historical production, the refilling phase and the storage operations are equivalent but with some peculiarities: the duration of primary production (12 vs 14 years) and the induced pressure drop (131 vs 90 bar); the duration and the strategies of the refilling phase (in case B, massive injection started immediately after the primary production, instead reservoir A had been affected for a considerable period by aquifer encroachment).

**Figure 5** Ground vertical movements ($\Delta u$) over pressure variations ($\Delta p$), for each cycle.

**Conclusions**

The scope of the research is to cast light on the deformation characteristics of underground formations involved in gas storage activities in the Italian Po Plain area. Two case studies were presented in terms of subsidence analysis via 3D numerical simulation approach. Thanks to the strong similarities between the two cases, in terms of structural and stratigraphic settings, formation lithologies, and UGS strategies, among others, a common correlation between induced pressure variation in each reservoir and corresponding ground movement was inferred based on an analogous deformation behaviour. The paper represents the first step in detecting a common deformation response, if any, sheared by the numerous UGS systems in the Po Plain basin.

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**References**


