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Ground subsidence phenomena in the Delta municipality region (Northern Greece): Geotechnical modeling and validation with Persistent Scatterer Interferometry

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ABSTRACT

Land subsidence is a common phenomenon occurring in several regions worldwide. Persistent subsidence causes strong consequences on the affected areas and related problems include environmental, economic and social aspects.

A set of forty-two Synthetic Aperture Radar (SAR) images, acquired in 1995–2001 by the European Space Agency (ESA) satellites ERS1 and ERS2, were processed with Persistent Scatterer Interferometry (PSI) technique to investigate spatial and temporal patterns of deformation in the Delta municipality (Thessaloniki plain, Northern Greece), a deltaic area with a long history of land subsidence related to aquifer system compaction.

Exploitation of output products of a PSI analysis, both average LOS (Line of Sight) deformation rates and displacement time series, revealed a large subsidence area due to intense groundwater withdrawal. Higher displacement velocities have been observed south-west of Kalochori and south of Sindos, from both sides of the Gallikos River. In those areas deformation rates of roughly 4.5 cm/yr have been recorded, during the period from 1995 to 2001.

Increasing subsidence rates are measured moving toward the mouth of the Gallikos River, where the thickest sequence of compressible Quaternary sediments is observed. Displacement time series retrieved by PSI technique has been compared with the temporal evolution of the deformation as measured by pre-existing leveling surveys, showing a great agreement.

A 2-D finite element model has been run along two representative cross sections in the Kalochori area, in order to simulate the observed temporal evolution of subsidence, coupling the geotechnical behavior of the formations and the piezometric surface level. Finally, results obtained by the subsidence model have been positively compared with the PSI-based information on displacement, providing accurate and perfectly verified results.

Outcomes of this work demonstrated the potential of repeat-pass satellite SAR interferometry (InSAR) as suitable technique for increasing knowledge about the extent and the rate of the deformations in case of subsidence events. Moreover, InSAR turned out to be a valuable tool to validate subsidence models and represents a cost-efficiency method, alternative to ground-based measurements for investigating surface deformation phenomena.

1. Introduction

Land subsidence induced by the overexploitation of aquifers is a very common natural hazard striking extensive areas worldwide and in many cases urbanized areas, causing remarkable economic cost annually. The Gioia Tuaro plain (Raspini et al., 2012) and Bologna (Stramondo et al., 2007) in Italy, the Anthemountas basin (Raspini et al., 2013) and the Thessaly plain in Greece (Kontogianni

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et al., 2007; Rozos et al., 2010), Murcia in Spain (Tomás et al., 2005), Mexico city (Osmanoglu et al., 2011) and Morelia (Cigna et al., 2012a) in Mexico, Tokio in Japan (Hayashia et al., 2009), Las Vegas (Amelung et al., 1999) and the Antelope valley (Galloway et al., 1998) in USA, Taiwan (Hung et al., 2010), Jakarta in Indonesia (Ng et al., 2012) and large zones in China (Xue et al., 2005; Zhang et al., 2011) are few examples of areas where subsidence caused by over-pumping has been identified and monitored. Review of occurrence, detection, measurement and mechanical models of the expected ground subsidence induced by aquifers exploitation are presented by Gambolati et al. (2005) and Galloway and Burbey (2011).

Despite the numerous bibliographic sources describing the land subsidence mechanism, the geotechnical simulation of the phenomenon is often a challenging task. The poly-parametric subsidence mechanism (involving geological, geotechnical, hydrogeological and many other components) and the overlapping of different sources of deformation (natural and human-related) make subsidence investigations complicated and require the intervention of multiple scientific specialties.

The territory of the Delta municipality, in the eastern sector of the Thessaloniki plain, is not an exception to the rule, as the study and even more the simulation of land subsidence phenomena in this area encountered several difficulties. The complexity of subsidence caused confusion among researchers leading to the proposition of a great variety of interpretations for the explanation of the phenomenon (Andronopoulos et al., 1990, 1991; Dimopoulos, 2005; Hatzinakos et al., 1990; Loupasakis and Rozos, 2009; Psimoulis et al., 2007; Rozos and Hatzinakos, 1993; Stiros, 2001). At the Kalochori village, the most affected area of Delta municipality, subsidence phenomenon took place for several decades, without being noticed at the beginning. This fact makes impossible retrieving detailed information of the total vertical displacements and, as a consequence, the conduction of back analysis for the calibration of the geotechnical simulation of the phenomenon.

The main objective of the current work, focusing on the land subsidence occurring in the Delta municipality, is twofold: to assess the contribution of the remote sensing data on the study of the phenomenon and to identify the main causes of the observed ground deformations.

The achievement of the first objective benefits of the recently retrieved Persistent Scatterer Interferometry (PSI) data (produced in the framework of the European Space Agency Terrafirma Extension project), which provide accurate historical information on range and rate of the subsidence, for a period of 6 years (1995–2001).

The second objective can be achieved thanks to the development of integrated methodology combining conventional in situ investigations and geotechnical modeling, run to simulate the land subsidence. The numerous studies conducted for the entire region provided plenty of data, covering all the requirements for setting up a finite element simulation model of the water pumping-induced subsidence phenomenon.

Finally, the availability of PSI data allowed the verification of the reliability and robustness of the results obtained with simulation.

2. Delta municipality: description of the study area

Located on the northern part of Thermaikos Gulf, the municipality of Delta covers an area of about 300 km^2, with more than 40 000 inhabitants. The municipality was formed in 2011 after the local government reform, by merging three former municipalities (Axios, Chalastra and Echedoros).

Thanks to its strategic position close to the Thessaloniki seaport, a natural gateway toward the Balkan Peninsula, this area experienced a rapid economic growth, becoming, during the 1960s, a flourishing industrial center in the region, accommodating the major part of industrial activity of the Thessaloniki plain. Many of those industries are heavy industries (i.e., skin processing, fabric industries and chemical industries), some others deal with animals slaughtering and food processing. All of these activities are high demanding from the water supply point of view. The villages of Kalochori and Sindos host the two main industrial areas of the municipality, developed straddling the Gallikos River, on its east and west side, respectively.

2.1. Geological and hydrogeological setting

The urbanized areas of Delta municipality have developed by occupying the easternmost sector of the Thessaloniki coastal plain, a delta formed in the last 2500 years. The plain is the largest deltaic area of Greece, with an extension of more than 1500 km^2. The landscape in the central part of the Plain is smooth, slightly dipping toward the sea, while close to the coastline it is flat.

The urban fabric of the Delta municipality, located at an elevation of few meters above sea level, developed above loose Quaternary deposits. These deposits, unconsolidated to partly consolidated marine-lacustrine sediments, filling a NW–SE oriented tectonic graben, consist mainly of sand and black silty clays (Hatzinakos et al., 1990; Rozos et al., 2004). The Neogene basement, buried by a 300–400 m thick sequence of Quaternary deposits, is represented by sandstones and red clays and outcrops in the north and in the north-east border of the area of interest (Fig. 1).

Thanks to the availability of several deep geotechnical boreholes drilled in the Kalochori region, Andronopoulos et al. (1991) classified the Quaternary formations in three horizons (sandy, silty and black silty clay). Rozos et al. (2004) reconstructed the architecture of the upper lithostratigraphic units, consisting of an uppermost sandy horizon lying over a silty clay layer and a deeper pattern alternating coarse and fine sediments.

With regard to the hydrogeological conditions, the above-described stratigraphic pattern led to the development of an unconfined shallow aquifer in the uppermost sandy horizon and of a system of deeper confined-artesian aquifers below the silty clay layer, characterized by very low hydraulic conductivity. Despite the presence of about 300 wells exploiting the shallower aquifer within the limit of Kalochori and Sindos village (Soulios, 1999), the level of the uppermost aquifer has not been affected by lowering, due the limited exploitation forced by the quite low quality of the water. Most of the wells are low-consumption and the extracted water is mainly used by the farmers for irrigation purposes or occasionally as drinking water for livestock.

On the contrary, since the early 1960s many deep water wells, exploiting the deep confined aquifers, have been drilled by the water company of Thessaloniki, to provide drinkable water to the city, and by the private companies to satisfy the flourishing industrial area. At the early 1950s, before the beginning of exploitation, the piezometric surface of this aquifer was above ground level and most of the wells were artesian. Continuous discharge and excessive consumption for about three decades caused a considerable lowering of the confined ground water table, which fell to a maximum depth of almost 40 m from the surface (Andronopoulos et al., 1990).

Because of the excessive problems caused by the land subsidence at the mid 1980s the water company decided to stop pumping water allowing the partial recovery (5–15 m) of the piezometric surface. Therefore, at the end of 1990s the piezometric level varied from 25 to 35 m below ground level (Soulios, 1999). According to measurements conducted between 1997 and 2001, the level