Land Subsidence Phenomena in Lowlands Occupied by Organic Soils. The Cases of the Densely Urbanized Coastal Cities of Messolonghi and Aitolikon (Greece)

N. Antoniadis[1], S. Alatza[2], C. Loupasakis[1], C. Kontoes[2]

1 School of Mining & Metallurgical Engineering, National Technical University of Athens, Athens, Greece
2 National Observatory of Athens, Institute for Astronomy and Astrophysics, Space Applications and Remote Sensing, BEYOND Center for EO Research and Satellite RS, Athens, Greece

antoniadis.nickolas@gmail.com

Abstract

The current study aims to focus on the surface deformation occurring in urban coastal areas founded on lowlands occupied by organic soils. The cities under investigation are Messolonghi and Aitolikon. Low-rate surface displacements have been reported along these sites, often resulting in building damages. The gradual subsidence of the sites combined with the climate change impact, resulted the last years to the occurrence of multiple floods. The rush of the sea water over the lowlands, has also been reported. The overexploitation of the underground water, the natural compaction of the under-consolidated clay soil layers, the consolidation due to the external loading of the constructions, the oxidation of the organic soils, the land use, the use of Synthetic Aperture Radar Interferometry (InSAR) and ground truth data were all examined collectively in order to comprehend this phenomenon. In the town of Messolonghi a variety of LOS deformation rates were recorded, with the maximum mean values in the eastern part (- 5mm/yr), whereas in Aitolikon the maximum values were in the range of - 4.5 mm/year. The displacements are mostly attributed to the building loads and natural compaction of the formations; however, it is evident that the increased precipitation rates and sea level rise, play a driving role in the occurrence of constant floods.

Introduction

The current study aims to focus on the surface deformation occurring in urban areas founded on lowlands occupied by organic soils. The cities under investigation are Messolonghi, a historical city of Greece, and Aitolikon, the so-called little Venice of Greece, which are located in Aitoloakarnania prefecture (Figure 1). In order to fully determine the phenomena occurring in these areas, results from the satellite data processing were examined together with the geological structure of the area as well as geotechnical study data gathered from a variety of sources.

Over the past few years, floodings and building damages have been reported in these rural areas. No previous research pertaining to the surface deformations and investigation of its causes, have been conducted to our knowledge. The study area is a densely populated environment, a fact that increases awareness towards this region and this phenomenon, as the risk and vulnerability from this geohazard are significant.

The gradual subsidence of the sites combined with the increasing mean annual precipitation rates, have resulted the last years to the occurrence of numerous floods. The rush of the sea water over the lowlands has also been reported. Both cities are densely populated and highly impacted by these displacements, which have resulted in numerous structural failures. These phenomena can be related with the exploitation of the underground water, the natural compaction of the under-consolidated clay soil layers, the consolidation due to the external loading of the constructions and the oxidation of the

organic soils. In the cities of Messolonghi and Aitolikon both uniform and differential settlements have been identified in many buildings, varying mainly in accordance to the foundation type.
The city of Messolonghi occupies a flat lowland and is founded on Quaternary formations consisting of fine grain sediments (clays, silts, and sands). On the other hand, Aitolikon was founded on an artificial island, constructed by earth fill materials deposited on top of 4 to 5 very small islands located in the center of the Aitolikon lagoon.

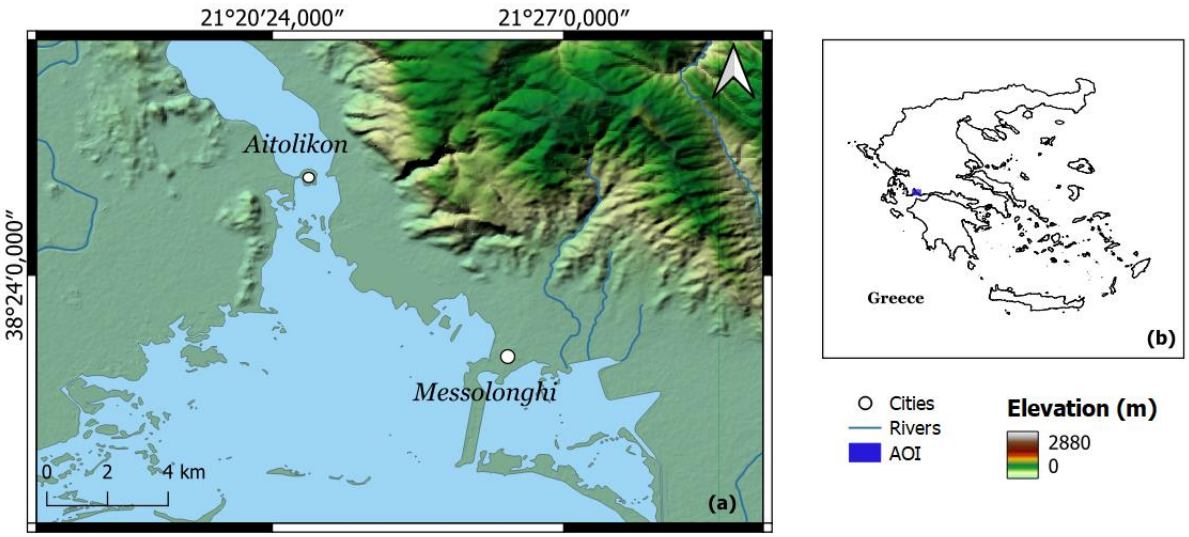


Figure 1. (a) The cities of Messolonghi and Aitolikon & (b) Location of study area

Methods

The investigation was divided into two phases:

Phase 1: Analysis of satellite data for a 7-year period (November 2015-February 2022)
The main tool for the analysis of the satellite data was the Stanford Method for Persistent Scatterers (StaMPS) (Hooper et al., 2007), enabling small-scale surface deformation monitoring over large time spans. Multi-temporal SAR (Synthetic Aperture Radar) interferometry is considered as a well-established method for monitoring ground displacements phenomena and is successfully applied in a variety of Earth deformation studies (Svigkas et al., 2020; Alatza et al., 2020[a], 2020[b]; Kontoes et al., 2021, 2022). 161 and 120 Sentinel-1A and 1B SLC images, from both descending and ascending satellite passes respectively, operated by the European Space Agency (ESA), were processed with the parallelized Persistent Scatterer Interferometry (P-PSI) processing chain (Papoutsis et al., 2020), developed in the Operational Unit BEYOND Center of EO Research and Satellite RS of the National Observatory of Athens (NOA). The estimated LOS (Line Of Sight) displacements provided insights on whether there is a considerable continuing hazard at the sites of interest. The timeseries exported during the investigation were also compared to the results presented from the European Ground Motion Service of Copernicus. The EGMS is the largest wide-area A-DInSAR service ever conceived. The EGMS aims to provide reliable information regarding natural and anthropogenic ground motion phenomena over Europe for the study of geohazards and human-induced deformation such as slow-moving landslides, subsidence due to groundwater exploitation or underground mining, volcanic unrests and many more (Costantini et al., 2021).

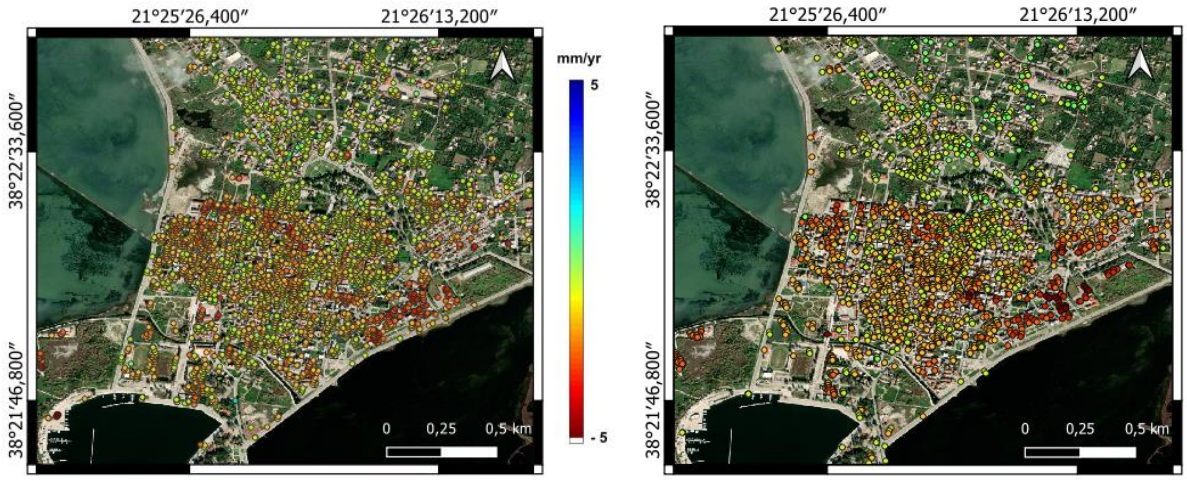
Phase 2: Analysis and statistical processing of all available geological and geotechnical data gathered from EAGME, Central Laboratory of Public Works and TCG archives. A total of 44 drilling profiles and over 100 oedometer tests were gathered for the city of Messolonghi. Moreover, field campaigns were carried out in these areas to record building damages.
The velocities of permanent scatterers combined geological, geotechnical, hydro-geological data, sea level rise and precipitation data validated the observed permanent scatterers negative velocities and enabled a more accurate interpretation of the phenomenon.

Results

As indicated in Figure 2 the deformation rates in Messolonghi vary. On the north part of the town the identified PS indicate relatively stable ground conditions, during the investigated time period, since the LOS values range from 0.3 – 1.3 mm/year. However, on other parts of the town the recorded deformations are higher. The east part of Messolonghi is an area with significant LOS deformations with a mean rate of −5mm/yr. The south and west parts of the town present a mean rate of -2.5mm/yr and -3mm/yr respectively. It is worth mentioning that the estimated subsidence rates increase towards the coastline.

Numerous buildings are affected by this subsidence phenomena, such as the buildings of Prefectural Administration of Aitoloakarnania, of the Port Authority and of the Public Finance Service of Messolonghi, as well as many residential buildings.

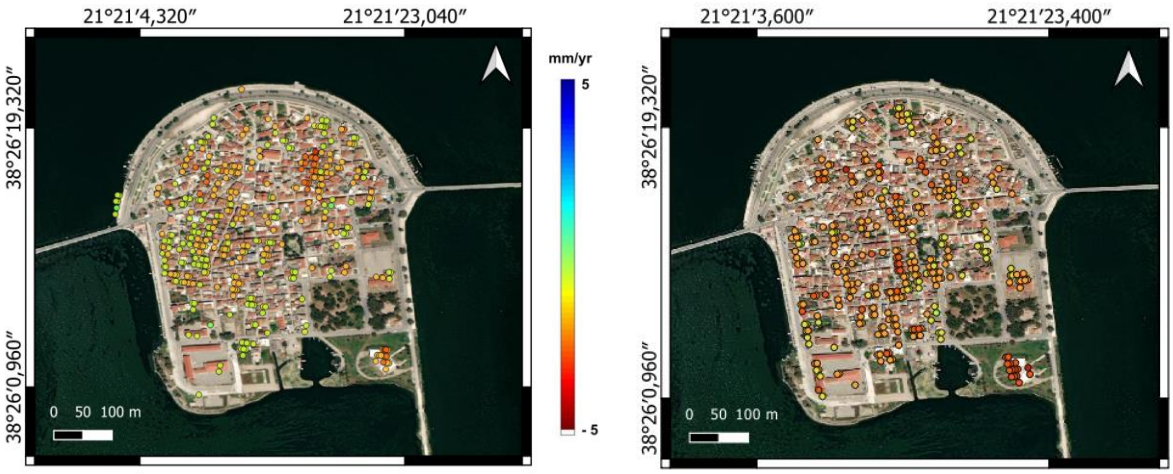
Drillings performed in the area indicate that the soil layers are extended horizontally along the site without any significant variations in thickness among which organic clay horizons with a thickness up to 5m, organic clayey silt to silt horizons, 5-10 m thick, and clayey sand to sand horizons with a thickness of 2-5m. The organic clay horizon contains a significant amount of plant residue and limestone fragments. According to laboratory tests that horizon is of low plasticity (I_p<14%) and can be described as soft to moderately stiff, with SPT values between 1 and 14. From the oedometer tests results it was discovered that the compression index values of those sediments are very high reaching up to 0.42. So, it is clear that the city is built on under consolidated formations subjected to subsidence due to natural compaction. Further investigations should be conducted for the identification of other co-acting mechanisms, such as ground water withdrawal or oxidation of organic soils.



(a) (b)

Figure 2. (a) Spatial distribution of the Sentinel-1 LOS deformations in Messolonghi for the descending satellite pass (no. 80); (b) Spatial distribution of the Sentinel-1 LOS deformations in Messolonghi for the ascending satellite pass (no. 175).

In the city of Aitolikon maximum LOS deformation values reach a mean rate of −4 mm/yr. The highest deformations are observed in the south part of the Island, where Vaso Katraki Museum is located (mean values of 4.5 mm/year). In the north part of the town significant damages to buildings have been recorded. It is worth highlighting that in that area the houses' foundations were in the water before the addition of the 1969 filling.



(a) (b)

Figure 3. (a) Spatial distribution of the Sentinel-1 LOS deformations in Aitolikon for the descending satellite pass (no. 80); (b) Spatial distribution of the Sentinel-1 LOS deformations in Aitolikon for the ascending satellite pass (no. 175).

Conclusion

The 2015–2022 Sentinel 1 datasets, as well as the data provided by the European Ground Motion Service of Copernicus, were exploited to monitor the surface deformation in the areas of Messolonghi and Aitolikon. The analysis of SAR data proved that subsiding is still ongoing with a steady rate in both sites. During the study, PSI, geological and geotechnical data were evaluated. The deformation signals indicated subsidence in various areas of both cities. The geological and geotechnical data validated that the formations are rich in organic material and they are still under consolidated. These deformations are related to the natural compaction and probably to the oxidation of the alluvial deposits. The effect of the ground water fluctuation is still to be examined.

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