Multi-sensor network for monitoring subsidence and seismic motion in Kalochori urban site, N. Greece

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Abstract
An urban-scale approach for monitoring seismic motion and ground subsidence has been implemented in the broader area of Kalochori, western of Thessaloniki in Northern Greece, by means of a multi-sensor network within the ongoing INDES-MUSA project (www.indes-musa.gr); funded by the Greek General Secretariat of Research and Technology. The integrated network combines land-based and airborne monitoring techniques covering a wide area of different urban sites such as residential structures, critical facilities and civil infrastructures like industries and oil tanks. The permanent monitoring scheme includes accelerometric stations collocated with reference GNSS stations, water level stations, a tide gauge mounted on a jetty of the Thessaloniki port and LiDAR missions of 25km2 flight plan covering the whole area under investigation. Field campaigns with mobile GPS sensors and water level measurements are also deployed periodically, in the framework of ground subsidence monitoring, whereas focused geophysical arrays were performed at the locations of the accelerometric stations to obtain knowledge on the subsoil conditions. Following a brief description of the area under study, salient features of the monitoring network components are described and some original data is presented with emphasis on shear waves propagation velocity models obtained from geophysical arrays, representative acceleration recordings from recent earthquakes in Greece and a Digital Surface Model of the area obtained from the first LiDAR mission.

Keywords: INDES-MUSA project; ground subsidence; earthquake recordings; collocated accelerometric-GNSS stations; LiDAR

1. INTRODUCTION

Risk and vulnerability of urban sites to natural hazards such as ground subsidence and earthquakes constitute an inherently spatial problem leading to an emerging need for urban-scale and highly-accurate monitoring schemes, continuous data acquisition and mapping solutions that can be readily employed by end-users and decision-making authorities for risk management, disaster preparedness and future urban planning. The above need is particularly important in the case of complex urban landscapes including different typologies of structures, critical facilities and civil infrastructures.

In this context, an integrated, multi-sensor network for monitoring ground subsidence and earthquake motion in a large-scale sense has been deployed in the broader urban area of Kalochori, located western of Thessaloniki city in Northern Greece, as part of the ongoing INDES-MUSA research project (www.indes-musa.gr). Following some historical evidence on the above natural hazards effects related to the Kalochori area, the general design concept, setting criteria and salient
features of the monitoring network are presented. Original data that has been acquired so far is also reported referring to new geophysical tests of Microtremor Array Measurements, acceleration recordings from recent earthquake events in Greece and a Digital Surface Model of the area under investigation obtained from the first LiDAR mission.

2. OVERVIEW OF KALOCHORI AREA

Subsidence effects in Kalochori were first noticed in the early 1960s, when the financial status of the region changed to a main industrial centre increasing rapidly the water needs met by productive wells. Overexploitation of the aquifers was further enhanced by the excessive water pumping by the Water Company of Thessaloniki. In support to the above, Stiros [1] reported that until the 1980`s, regions presenting maximum ground subsidence (larger than 3m) coincided with the areas containing the pumping wells of the Water Company of Thessaloniki and with the south-western section of the industrial area containing the most water-consuming industries. More recently, Badelas et al. [2] measured a subsidence rate from 3 to 13 cm/yr based on geodetic surveys conducted from 1992 to 1995. Nowadays, extensive areas along the coastline are located below sea level, having a mean rate of subsidence in the order of 3–5 cm/year (Mouratidis et al. [3]). Further information on historical evidence of ground subsidence in the area of Kalochori may be found in Loupasakis & Rozos [4] and Raspini et al [5].

Kalochori is also close to a seismically active region including the metropolitan city of Thessaloniki (Paradisopoulou et al. [6]) which has experienced several destructive earthquakes (M6.2 to M7.5) during its 23 centuries of continuous history. The strong M6.5 earthquake of 20/06/1978 occurred at an epicentral distance of 30 km east of Thessaloniki causing fifty deaths, severe damages on 25% of the building stock and serious social–economic losses. With reference to geological aspects, the region of Kalochori constitutes a tectonic graben covered by Quaternary and Neogene deposits of great thickness, consisting mainly of marine and lacustrine sediments. According to Nikolaou & Nikolaidis [7], these deposits extend to a depth varying from 150 to 400m whereas deeper soil layers consist of Neogene deposits until the depth of 600–700m.

3. INDES-MUSA MONITORING NETWORK

INDES-MUSA monitoring network is comprised of permanent GNSS and accelerometric stations, mobile rover GNSS stations, permanent and mobile water level stations and a tide-gauge station. A general overview of the monitoring scheme referring to the permanent installations is given in Figure 1 allowing integrated observations of ground subsidence and seismic action. Among the innovative features of the monitoring scheme is the implementation of airborne Light Detection And Ranging (LiDAR) missions to monitor surface topography changes and produce a 3D city model of the area under investigation. In this manner, a region of more than 25km² is monitored including the complex urban environment of the broader Kalochori area. In this regard, three urban sub-zones (i.e. the residential buildings zone, the industrial zone and the oil tanks zone) and a free-field zone away from the build environment have been geographically defined, allowing treatment of each sub-area as a homogenized urban unit having similar structural types and urban densities. The approximate boundaries of the above sub-areas are highlighted in Figure 1.

3.1 Permanent network: Accelerometric stations, GNSS base stations and a tide gauge system

A pair of REF TEK 130-SMA accelerometric stations is installed in each sub-zone comprising of a “structural” (denoted with S) and an “urban reference” (denoted with UF) station, respectively. The former refers to an accelerometric station installed at the top of a representative structure of each sub-zone, whereas the latter refers to a ground installation (either on open ground or in a small structure) where minor contamination of earthquake recordings is anticipated by the dynamic
response of adjacent structures. Another accelerometric station (KLH7 in Figure 1) is foreseen to be installed on open ground at the opposite side of Kalochori bay representing a free-field reference station. The main features of the accelerometric network are summarized in Table 1. All the stations are oriented in the N-S direction and operate on a continuous recording basis with real-time data transfer to a central data acquisition server installed in EPPO-ITSAK premises in Thessaloniki. Two accelerometric stations (KLH1 and KLH3) are collocated with GNSS reference stations. Therefore, correlation of accelerometric and GPS data by the collocated stations is feasible, providing valuable information for investigating seismic motion especially for the identification of near-field effects and long-period pulses (Emore et al. [8]). GPS observations are archived at 1Hz on a daily basis allowing for derivation of time-series positions and velocities and for RTK applications. The permanent monitoring network is complemented by a tide gauge station installed on the southeast jetty of Thessaloniki port (TG1 in Figure 1) providing sea level measurements at 15min intervals and two water level stations that are planned to be installed in properly selected inactive boreholes (WL1 and WL2 in Figure 1).

3.2 Mobile network: rover GNSS stations and water level stations

Within ground subsidence investigation, INDES-MUSA project mobile monitoring network includes thirty three (33) water level measurement points and eighteen (18) GNSS rover stations.
covering the test site of Kalochori (Figure 2). With reference to the water-level measurement points, the inactive drills composing the network were carefully selected among others to satisfy two main conditions: a) to reach deep down to the confined aquifers (larger than 50m in depth) and b) to pass the shallow unconfined and low quality aquifer without draining it. So all selected drills indicate the GW level of the deep and heavily damaged by the overexploitation successive confined aquifers. Water level measurements have started and will be performed for two years during the highest and lowest ground water level periods (May and October). The produced isopiezometric maps will be correlated with the surface deformations recorded by the GNSS stations and the LiDAR missions.

3.3 Airborne LiDAR mission

The first LiDAR mission (Figure 3) was performed on 2nd of May 2014 covering a 25km² flight plan over the area while the aerial photography acquisition was performed on 11/05/2014. Upon the issuance of the proper flight permission from the Hellenic Defence General Staff flight missions were scheduled based on high resolution cloud coverage meteo forecast on 3 hours time intervals from Meteo Lab of the University of Athens. Flight Planning for both sensors was conducted using modern software tools allowing best fit to the geometry and terrain relief of the area. Flight & Sensor Control Management System provided precise flight guidance, an intuitive interface for sensor operation and data quality control during laser and imagery data acquisition. With the use of Leica ALS60 Airborne Laser Scanner, Multiple Pulses in Air (MPiA) sensor there was production of High Density Surface Models (DSM) and DTM at a 1x1 m grid spacing. The process for resolving the lidar trajectories and the computation of the point clouds produced a highly accurate DSM and generated realistic 3D+ environments and Info Clouds containing elevations (Figure 4). The combination of DSM/DTM with Airborne Color Imagery acquired with the Z/I DMC gave accurate orthomaps production. The imagery from the DMC native 1:1 color resolution (RGB) was ready for the exploitation process within the end-to-end workflow with use of GPS/INS. After post-processing, the imagery was brought into all stages of the photogrammetric workflow – aerotriangulation and orthorectification at pixel size 0.1m at engineering-scale accuracy. Precise sensor stabilization during camera exposure was essential for good quality. The post-processing has...
used the concurrent data of the 2nd May from the two GPS GNSS base stations of the project and the 57 GCP measured with GPS GNSS. It was a very dense and accurate GPS campaign in the area of Kalochori. The accurate 3D city model of the region obtained from the LiDAR data will allow compilation of a building stock inventory in terms of structural height and plan dimensions.

Figure 3. LiDAR mission equipment (pictures taken on 2nd of May 2014)

Figure 4. 3D city model images related to the three sub-zones within the investigated area of Kalochori

4. ORIGINAL DATA AND RECORDINGS

A set of representative recordings that have been acquired so far from the INDES-MUSA accelerometric network and some original data are presented in this section. Along these lines, a series of in-situ geophysical arrays was performed by implementing the Microtremor Array Method (MAM) (Aki & Richards [9]) to obtain knowledge of the subsoil conditions within each sub-zone of
the Kalochori site. For this reason, Guralp CMG-6TD systems were employed to acquire microtremor data comprising of a 24-bit digitizer and a seismic sensor. The latter is a three orthogonal component broad-band (30 sec to 100Hz) velocity-meter of high sensitivity. Sampling rate was set at 100 samples per second implementing a few hours of continuous recording. The seismic sensors were installed in circular arrays of different radius (one station was permanently

![Figure 5](image-url)

**Figure 5.** (a) Shear wave velocity profiles obtained within each sub-zone of the Kalochori area using MAM (b) Locations of epicentres of four recent earthquakes in Greece recorded by the INDES-MUSA accelerometric network

![Acceleration time histories](image-url)

**Figure 5.** (a) Acceleration time histories (E-W component) of Cephalonia M6.0 (26/01/2014), Cephalonia M5.9 (03/02/2014), N. Aegean M6.9 (24/05/2014) and Thessaloniki M3.0 (16/07/2014) earthquakes recorded at KLH4 station (b) Accelerations time histories (U-D component) of Thessaloniki M3.0 earthquake (16/07/2014) recorded at KLH3, KLH4, KLH5 and KLH6 stations.
installed at the center of each circle) taking into account the urban environment and available geo-
data. Within the industrial zone, the oil tanks zone and the free-field zone, the geophysical arrays
were deployed in less than 100m distance from the corresponding accelerometric stations. For the
residential zone the dispersion curve data reported in Manakou et al. [10] was adopted. Shear wave
velocity profiles obtained within each sub-zone are given in Figure 5a. The above data in
conjunction with earlier studies on the subsurface structure in the broader Kalochori area (Raptakis &
Makra [11]) will be utilized in a future analysis stage to set up representative one-dimensional
soil models for site response analysis under properly selected earthquake scenarios. In this regard,
four recent earthquake events in Greece (Figure 5b) have been recorded to this end by the INDES-
MUSA accelerometric network referring to the Cephalonia earthquakes M6.0 and M5.9 of January
26th and of February 3rd 2014, respectively, the N. Aegean M6.8 earthquake of May 24th 2014 and
the Thessaloniki M3.0 earthquake of July 16th 2014. The corresponding acceleration time histories
(E-W component) recorded at KLH4 station are shown in Figure 5a reflecting the different
characteristics of the seismic motion in terms of amplitude, duration and frequency content. With
reference to Thessaloniki M3.0 earthquake, recordings from four accelerometric stations are given
in Figure 5b, corresponding to the U-D component. The significant amplification of seismic motion
recorded at the top of the instrumented structures (KLH3 and KLH5 stations) with respect to the
“urban reference” recordings (KLH4 and KLH6 stations) is evident.

5. CONCLUSIONS AND PERSPECTIVES

A multi-sensor network deployed in the area of Kalochori, west of Thessaloniki, to monitor ground
subsidence and seismic motion, was presented as part of the INDES-MUSA project. Both airborne
and land-based monitoring solutions are adopted. The main features of the network components
were described followed by a preliminary presentation of recently produced original data and
recordings as part of the INDES-MUSA database. The latter will be further enriched with ground
subsidence measurements and (when available) earthquake recordings, to be integrated with
analysis of ground subsidence mechanism and soil-structure interaction effects in an urban scale
and deliver a Web-GIS data portal that will be made available to end users.

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