Establishment of an Integrated Landslide Early Warning and Monitoring System in Populated Areas

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Abstract

In this work a complete permanent system of timely landslide warning and monitoring in Greece is presented. This system is the first that is designed for a densely residential and mountainous environment. Since 1960's several instability phenomena have been recorded in one of the most traditional settlements in Greece, Metsovo, Region of Epirus. The last major landslide event occured in 2010–2011, and lead to serious damages on the construction and infrastructure within the settlement. The wider geological regime consists of Olonos-Pindos formations with the main appearance of the flysch one of the most critical landslide prone geological formations in Greece. The combinational use of dynamic geotechnical and satellite research methods is discussed as part of this study. In addition, one of the main goals of this investigation is to combine long term monitoring of the parameters connected to the landslide activity with the observation of the landslide kinematics in real time for the planning and realization of a Landslide Early Warning System (LEWS) in Greece.

Keywords

Greece • Real-time • Monitoring • Landslide early warning systems (LEWS)

Introduction

Landslide phenomena are included in the natural hazards with serious socio-economic consequences and with a considerably increasing number of events in the last years, as much internationally as nationally, mainly because of the intense anthropogenic intervention in the geo-environment but also because of the frequent appearance of extreme meteorological events. Characteristically, from 2000 and on, an increase that exceeds 25% has been observed in recorded landslide events in Greece (Sabatakakis et al. 2013).

The monitoring and recording of the kinematics preceding of the activation or reactivation of a landslide, with the application of geotechnical and remote sensing methods, with real time measurements is an increasingly important area in landslide studies (Corsini et al. 2007; Bobrowsky et al. 2015; Casagli et al. 2017) and seems to conclusively contribute to the quick evaluation of its style of activity (WP/WLI 1995). Overall, this knowledge can constitute a basic tool for the creation of a sufficient and reliable evaluation model for the landslide risk, with application in populated areas and in areas of linear or point infrastructures.

In Greece, and in particular on the western part, large landslides have taken place, causing extended destruction to large road axes and to mountainous settlements. Besides, as it results from the landslide susceptibility map of Greece (Sabatakakis et al. 2013), the larger part of Western Greece is classified as "high" to "extremely high" susceptibility.

The pilot application of a complete permanent system of landslide early warning and monitoring is presented in this work, with the combinational use of dynamic geotechnical

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and remote sensing methods. The pilot area corresponds to a densely built mountainous village of the Region of Epirus, known as the Metsovo village. This application is the first that has been realized in a Greek territory and in particularly in a densely residential environment. Preliminary results from the application of a similar combinational system with the use of static geotechnical and remote sensing methods for another region of Western Greece, have been published by Nikolakopoulos et al. (2017).

The differentiation and innovation of the present work lies at the fact that for the first time in Greece, all the known kinematic monitoring techniques (geotechnical, interferometry, satellite geodesy, remote sensing) are combined on a “real-time” level for the evolution of the landslides in residential areas. The measurement data and results of these techniques are transferred on real time to storage stations and with the proper treatment directly on a specially formed internet platform (WebGIS). Then the collected data are ready to be used by a wide spectrum of scientists of competent entities that occupy themselves with landslide risk management issues. This process reflects to the principal data basement and is the first step of planning and realization of a landslide early warning system (LEWS) in Greece.

Study Area

The Metsovo village, Region of Epirus, is built on 1060–1200 m of altitude on the eastern side of the mountain range of Pindos. It is a traditional settlement of about 2500 permanent residents with high touristic activity “Fig. 1”.

From the geological point of view, the wider area of Metsovo belongs to the overthrust front of the Olonos–Pindos zone with the main appearance of the flysch formation in various phases (Zouros and Mountrakis 1991). The main geological basement is the medium-thick sandstone horizon of flysch, interbebbed with thin grey horizons of siltstone. Deeper layers consist of clay-sandstone comprising interchanges of fine-grained sandstone and siltstone. Because of the tectonic deformation that the latter has been submitted due to an internal thrust in Flysch, in combination with the intense morphological relief of the study area, serious instability problems are generally caused in various positions around. These instabilities are expressed as individual landslides in the weathering zone of Flysch. Furthermore, the high percentages of rainfall observed in the area with average yearly rainfall of 1472 mm (Koumantakis 2011), mainly during the wet period and the appearance of a considerable number of springs, favour the slope instabilities in such types of formations.

Since the 1960’s until today, landslides have been observed in the settlement with direct impact in the infrastructure and the daily life of the residents. In particular, the main landslides examined in the present study are two and are located on the southern part of the residential area at the neighbourhoods of Agios Dimitrios and Agios Charalampos. The most serious activation for both the partial landslides took place on 2010 “Fig. 1” with the appearance of fracturing and subsidence in the streets and infrastructure as well as fracturing in houses, some of which are considered as decrepit. According to the inclinometer measurements taken on both neighbourhoods since 2010 until today, the movement seems to evolve with very low velocity values, thus the landslides can be characterized as “extremely slow” (WP/WLI 1995). More precisely, mean rates of movement ranged from 7–8 mm per year at Agios Charalampos and 10–12 mm per year at Agios Dimitrios.

In the context of the present project, a rich archive of studies, technical reports, scientific projects and reports on the local press was gathered, which was evaluated for the better approach of the problem and the proper organization and planning of the landslide observation system.

Establishment of the Landslide Monitoring System

The observation and analysis of the landslide characteristics on a large scale (site-scale, >1:500) takes into consideration some specific criteria (Corominas et al. 2014; Soeters and van Westen 1996). The selection of the settlement of Metsovo as a pilot area for the installation of a complete observation system of the landslides covers these criteria to a great extent, because: (a) it is a residential area with important infrastructure works at risk, (b) the research areas are smaller than 0.1 km^2 and focus on periodically activated landsliding zones, (c) a relatively sufficient knowledge of the engineering geological and geotechnical conditions of the subsoil and the geometry of the unstable areas is available and (d) the geomaterials participating in the phenomenon belong to geological formations “prone to landslides”. Analyses in this research scale permit the subsequent development of landslide early warning systems (LEWS) exploiting the phenomenon monitoring data (Pecoraro et al. 2019).

The installed landslide monitoring system basically provides insight into the evolution of surface and subsurface movements with the combinational use of measurements of

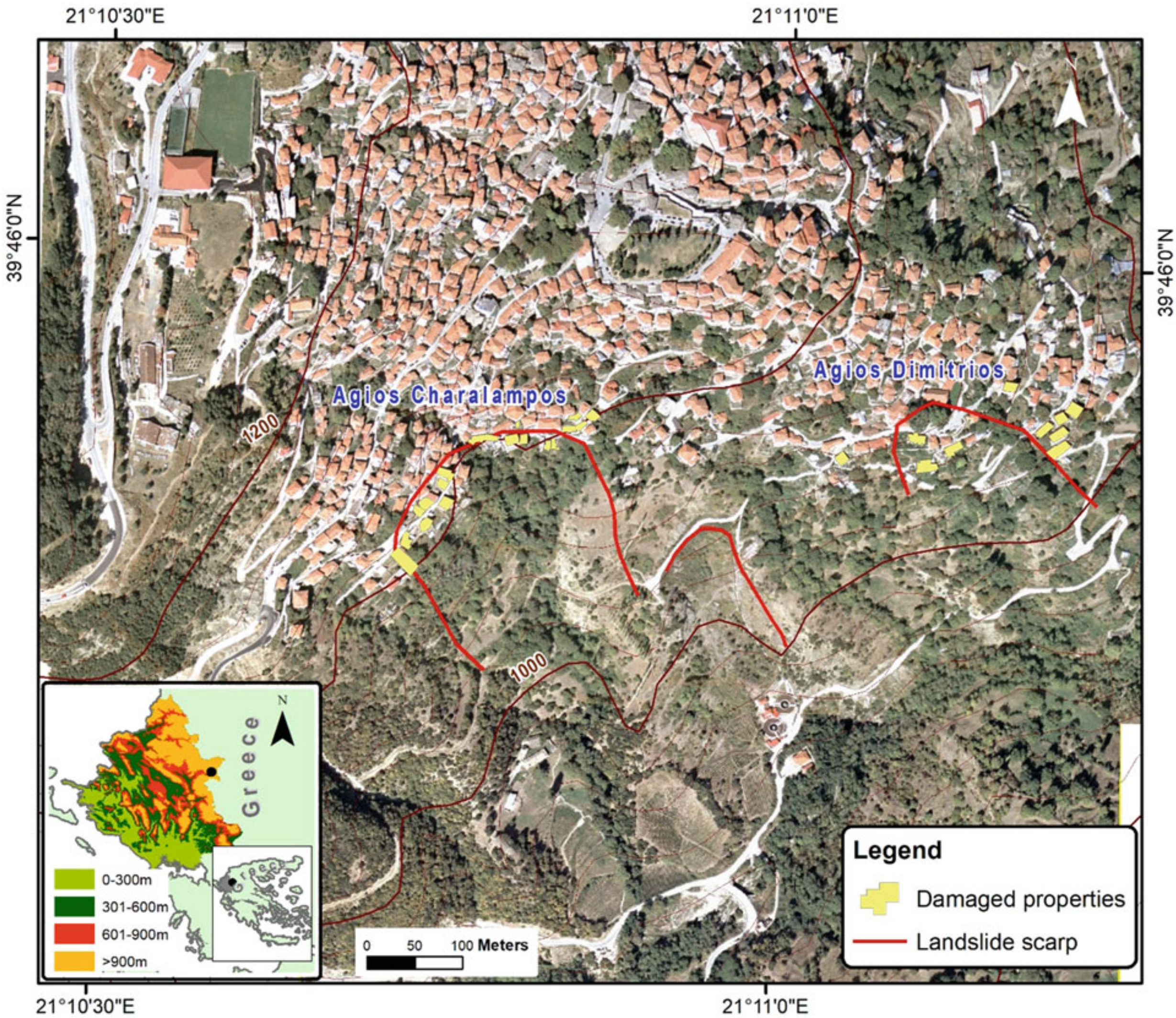

Fig. 1 Location map of the Metsovo settlement and landsliding areas. The colours of the inserted map refer to the different elevation classes in the Epirus region

geotechnics, interferometer, satellite geodesy and remote-sensing with the parallel real-time monitor of rainfall, as it seems that landslides are directly connected with intense and extended rainfall phenomena "Fig. 2".

Persistent Scatterers

Persistent Scatterer Interferometry (PSI) is an approach of interferometry for monitoring Earth's surface, as it is able to measure microscale displacements in terrain surface. In addition, this application permits the measurement of surface deformation over vast areas with at a frequency varying from one month to several days with the earliest satellites (Raspini et al. 2019). For this purpose, five (5) scatterers were installed in several positions of the study area and satellite receptions were programmed with a frequency of eleven (11) days. More specifically, the scatterers are corner retro-reflectors consisting of perpendicularly intersecting flat surfaces and they are mainly made of aluminium, for easy transportation and installation.

Permanent GPS Stations

Permanent GPS stations can monitor the surface deformations (Gili et al. 2000). The GPS network consists of 2 permanent stations. One of them was installed in a stable area, while the other one into the landslide zone. The stations continuously record the land deformation and the data are transferred in real time to data storage station (NAS server). Thus, at any given time, the relative position as much of

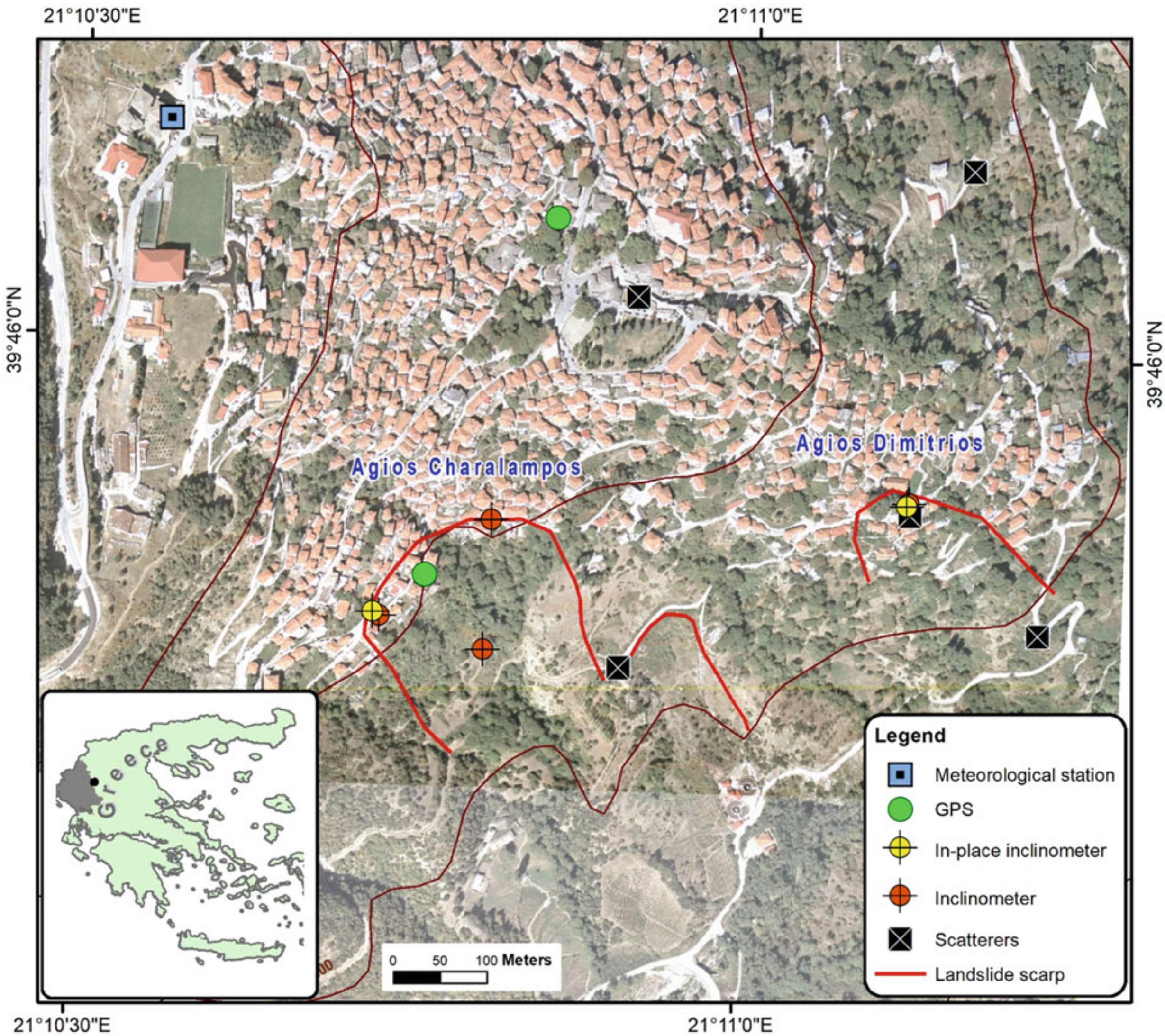

Fig. 2 The permanent landslide monitoring system

scatterers as the position of the GPS station located in the landsliding area will be determined in relation to the stable stations. A characteristic example of application of this method constitutes the observation of slopes in southern Apennines, Italy (Calcaterra et al. 2012).

Unmanned Aerial Vehicle Surveys

They are used for the exact determination of the land topography, the photogrammetric survey on selected points of the pilot area and the creation of photomaps and Digital Surface Models (DSM) of high precision. These data can also be used as much as basemap for the remaining studies as for the exact measurement of changes on the relief in case of land movement. Different studies demonstrating the use of UAV data for landslide monitoring have been published in Rau et al. (2011), Turner et al. (2015) and Nikolakopoulos et al. (2017).

Meteorological Station

The meteorological station is located inside the settlement very close to the landslide area. Rainfall constitutes a basic factor for the initiation of landslides (Sabatakakis et al. 2005; Guzzetti et al. 2008; Lainas et al. 2016) and therefore the pluviometric data are continuously recorded and sent to the data storage station (NAS server) in real time. The recording of rainfall events with the parallel observation of the landslide evolution rate will permit on the following stage, the determination of critical values of rainfall thresholds that activate the landslides, and which will constitute an important factor for the formation of the type of warning of EWS.

Inclinometer Boreholes

A network of eight (8) drilling inclinometers has been installed in the research area that permits the detailed observation of subsurface displacements, for an extended period of time. In two of them inclinometers have been permanently placed (in-place) aiming to the observation in real time of the movement, the data of which are continuously recorded and sent to the data storage station (NAS server). Further analysis of the subsurface displacements time series in combination as much with the surface movement as with the rainfall time series will lead to the full understanding of the evolution rate of the phenomenon. The determination of critical speed thresholds, the exceeding of which can cause noticeable deformations that it is likely to affect the local society, will also constitute a parameter of the EWS.

Discussion–Conclusion

Many mountainous villages have been struck by landslides in western Greece due to growing urbanization and uncontrolled land—use in landslide—prone areas, without considering the engineering geological environment. The presence of the tectonically highly sheared and weathered geological formations of the alpine basement (such as flysch) and the intense geomorphological relief, strongly contribute to the periodically induced instability phenomena mainly triggered by heavy rainfalls and extreme meteorological events.

The study site of Metsovo village, constitutes a typical example of a mountainous, touristic settlement with intense anthropogenic activity, periodically stricken by landslide phenomena that caused severe damages in houses and infrastructures. The installation of a permanent complete system for landslide kinematics observation consisting of persistent scatterers, permanent GPS stations, UAV, meteorological station and in place inclinometers, constitutes the first step for an EWS establishment in Greece.

The obtained results of the system measurements will be appeared in almost real time, in interactive way through a specially designed internet platform (WebGIS). That will constitute a powerful tool for the local authorities and the residents of the area in case of emergency.

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