Preliminary results from active landslide monitoring using multidisciplinary surveys

Konstantinos Nikolakopoulos, Katerina Kavoura, Nikolaos Depountis, Aggeliki Kyriou, Nikolaos Argyropoulos, Ioannis Koukouvelas and Nikolaos Sabatakakis

Department of Geology, University of Patras, Patras, Greece

ABSTRACT
This study presents the synergy of multidisciplinary surveys for the monitoring of an active landslide in Western Greece. The aim of this paper is to highlight and validate a methodology based on multiple sensors data integration which can successfully be used to manage natural disasters or to improve the knowledge of a specific phenomenon in order to prevent and mitigate the risk. Photogrammetric and interferometric processing has been applied to a complex set of remote sensing data such as high resolution satellite images, digital airphotos, aerial photos acquired from an Unmanned Aerial Vehicle and radar data. Global Navigation Satellite System measurements and continuous inclinometer measurements are being performed. The multifunctional technology of Geographic Information Systems is used in order to collect, storage, manage, process, analyze and cartographically represent the previously described complex geoscientific information.

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Introduction
An active landslide can be monitored using many different methods: classical geotechnical measurements like inclinometer, topographical survey measurements with total stations or Global Navigation Satellite Systems (GNSS) receivers, Airborne Light Detection and Ranging (LiDAR) systems, Terrestrial Laser Scanners (TLSs), photogrammetric techniques using airphotos or high resolution satellite images, Differential Interferometry using radar images (DInSAR) and recently computer vision techniques using data from Unmanned Aerial Vehicles (UAVs). Wieczorek and Snyder (2009) analyze the advantages and drawbacks of many different methodologies for landslide monitoring such as measurements tapes or GNSS, extensometers, inclinometers, aerial photos, LiDAR and DInSAR techniques. For proper displacement identification all the earlier methods need a high resolution and a very accurate representation of the relief. Performing repeated surveys is necessary for an active landslide monitoring as the geomorphology of a landslide must be analyzed and the changes over time should be mapped precisely (Barbarella, Fiani, & Lugli, 2015; Travelletti et al., 2012).

TLS instruments is a very effective technique providing huge amounts of measurements in short time and improving our understanding for changes and deformations of a landslide (Barbarella & Fiani, 2013; Castagnetti, Bertacchini, & Rivola, 2014; Spreafico et al., 2015). The aforementioned techniques present some drawbacks. Particularly, the topographic surveys are time-consuming and have sparse spatial coverage, which results in the omission of fine-scale terrain structure in the resulting Digital Surface Model (DSM) as described in a previous study (Martha, Kerle, Jetten, Van Westen, & Kumar, 2010).

TLS provides highly dense and accurate point clouds, but the deployment of such surveys can be time consuming and – sometimes – very difficult when having to deal with very steep terrain while airborne LiDAR is quite expensive for individual landslide studies (Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012). Airphotos or satellite data and image analysis techniques can be an alternative solution for landslide mapping and monitoring (Fabris, Menin, & Achill, 2011; Mondini et al., 2011; Nichol, Shaker, & Wong, 2006). They present the advantage of covering broader areas within one scene and the drawback of repeatability as the purchase of very high resolution satellite data and the airplane campaigns are quite expensive. Photointerpretation and very high resolution optical satellite data are used to detect individual landslides or groups of slides (Fiorucci et al., 2011; Marcelino, Formaggio, & Maeda, 2009; Metternicht, Hurni, & Gogu, 2005). Most commonly, change detection techniques applied to high resolution and very high resolution optical images are used to
identify landslide areas (Lee & Lee, 2006; Nichol & Wong, 2005; Tsai, Hwang, Chen, & Lin, 2010; Weirich & Blesius, 2007). The change detection technique presupposes the existence of two (pre-event and post-event) images for the landsliding area. Digital image analysis techniques for mapping landslides and monitoring related elevation changes from repeated Digital Elevation Models are comparably often applied (Chandler, 2001; Maas & Kersten, 1997; Mantovani, Soeters, & Van Westen, 1996; Nikolakopoulos, Vaiopoulos, Skianis, Sarantinos, & Tsitsikas, 2005; Weber & Herrmann, 2000). Some other studies focused mainly on the use of remote sensing data on horizontal displacement measurements (Baum, Messerich, & Fleming, 1998; Kääb, 2000; Martha et al., 2010; Powers, Chiarle, & Savage, 1996).

Inclinometer is one of the most commonly used monitoring devices for measuring tilt which is used in several calculations (computations) to quantify displacement and deflections of slopes, embankments and structures. A hollow metal or plastic tube is installed within a drilled hole, which can then be periodically measured to determine the variation of the original inclination of the tube (Wieczorek & Snyder, 2009). Ideally, the subsurface location of a landslide rupture can be detected with the inclinometer. Furthermore, the method determines in detail the depth of slide surface, the magnitude, rate and direction of landsliding movement (Machan & Bennett, 2008; Stark & Choi, 2008). Long-term observations describe in a good way the slope behavior within a borehole network. Thus, the kinematic changes may occur in the evolution of a landslide could be easily determined and then linked with triggering parameters of the landslide, such as heavy rainfall and/or seismic activity (Cascini, Calvello, & Grimaldi, 2014; Kavoura, Sabatakakis, & Tsiambaos, 2016; Macfarlane, 2009). There are numerous studies that different monitoring techniques and inclinometers were applied together in cases of large landslides in order to understand the landslide partners of movement, as well as their mechanism (Calceterra et al., 2012; Di Maio, Vassallo, Vallario, Calceterra, & Gambino, 2013; Marcato, Mantovani, Pasuto, Zabuski, & Borgatti, 2012; Massey, Petley, & Mc Saveney, 2013).

The continuous evolution of satellite radar sensors has led to the development of a technique capable to generate maps of ground surface deformations measured with millimeter precision. DInSAR has also been tested in landslide monitoring. At an early step, attempts on land deformation through interferometry took place with data from ERS-1/ERS-2 missions (Gens & Van Genderen, 1996), while land subsidence monitoring using ERS data was applied in Germany, Mexico and Italy with the same aim (Strozzi, Wegmüller, Tosl, Bitelli, & Spreckels, 2001). In a respective study, ERS, Envisat ASAR data and a limited set of high resolution TerraSAR-X data were acquired and they were submitted to interferometric process for deformation monitoring in a Czech area (Lazecký, Rapanta, Perissinb, & Bakoñ, 2014). Furthermore, in the southeast of China, the Small Baseline Subsets DInSAR technique was applied using Cosmo-SkyMed data and it led to reliable results (Rao & Tang, 2014). Persistent Scatterer Interferometry (PSI) is another approach of interferometry which may contribute in subsidence mapping with effective results with millimeter accuracy (Crosetto, Monserrat, Cuevas-González, Devanthéry, & Crippa, 2016; Rosi, Agostini, Tofani, & Casagli, 2014; Strozzi et al., 2001; Righini, Raspini, Moretti, & Cigna, 2011; Tofani, Raspini, Catani, & Casagli, 2013). PSI using ERS-1/2 and Envisat data has been applied for landslide monitoring in the Italian Alps (Del Ventisette, Righini, Moretti, & Casagli, 2014). The same approach was exploited different SAR data and the results were associated with GNSS data (Bovenga, Reiffce, Pasquariello, Nitti, & Nutricato, 2014; Colesanti & Wasowski, 2006; Crosetto et al., 2013). The PSI technique was also combined with in situ geological and geomorphological evidences as well as with standard geodetic methods, yielding to precisely update ground movements in high instability of Gimigliano area in Italy and a respective area in Lithuania (Bianchini, Cigna, Del Ventisette, Moretti, & Casagli, 2013; Ćyzieńe, Minkevičius, Mikulėnas, & Satkūnas, 2012).

The newest method for landslide monitoring is the use of ultrahigh resolution imagery captured from UAVs. The use of UAVs for research purposes has become possible and cost affordable due to technological developments such as autopilot systems, lightweight action cameras, miniature GNSS, advances in carbon fiber airframes and the simultaneous development of new processing methodologies based on computer vision like the Structure from Motion (Lucieer, De Jong, & Turner, 2014; Nikolakopoulos et al., 2015a). Instead of using the analog airphoto stereopairs with overlap along the flight path, the Structure from Motion process starts by acquiring photographs of the object of interest with sufficient overlap (e.g. 80–90%) from multiple positions and/or angles. Based on advances in image feature recognition, such as the Scale Invariant Feature Transform (Lowe, 2004), the common points are automatically detected and matched between photographs. A bundle block adjustment is then performed on the matched features to identify the 3D position and orientation of the cameras, and the XYZ location of each feature in the photographs resulting in a sparse 3D point cloud (Šnävely, Seitz, & Szeliski, 2008; Triggs, Mc Lauchlan, Hartley, & Fitzgibbon, 2000).
Several recent studies have also demonstrated the power of Structure from Motion algorithms for landslide mapping and monitoring (Niethammer, Rothmund, Schwaderer, Zeman, & Joswig, 2011; Akca, 2013; Lucieer et al., 2014; Nikolakopoulos et al., 2015a; Turner, Lucieer, & De Jong, 2015). Different studies demonstrating the use of UAV data for landslide monitoring have been published (Lin, Tao, Wang, & Huang, 2010; Rau, Jhan, Lob, & Linb, 2011; Turner et al., 2015).

Taking into account that a single technique is not always sufficient to perform reliable and accurate measurements, synergistic use of more than one system was performed in the past for landslide monitoring. Landslide monitoring should be accomplished by field-based geodetic, geotechnical, geophysical techniques and remote sensing techniques (Corsini, Borgatti, Coren, & Vellico, 2007). In that study, two LiDAR campaigns on board helicopter were performed in the Northern Apennines, Italy. In a similar study (Niethammer, James, Rothmund, Travelletti, & Joswig, 2012), the UAV capability for imaging fissures and displacements on the landslide surface has been evaluated. The accuracy of the UAV imagery-derived DSM was compared to a DSM created from TLS. The simultaneous measurements from Automated Total Station (ATS), GNSS and ground-based SAR Interferometry were processed for the monitoring of an active landslide located in the northern Apennines of Italy (Castagnetti, Bertacchini, Corsini, & Capra, 2013). Diverse imaging systems and UAVs among other airborne platforms were used to acquire very high resolution images of the Super-Sauze mudslide in the Barcelonnette Basin in the Southern French Alps at five different dates (Stumpf, Malet, Kerle, Niethammer, & Rothmund, 2013). In another study, the spatial integration of multiple remote sensing techniques, such as Airborne Laser Scanning (ALS), TLS, ATS and GNSS, was performed (Castagnetti et al., 2014).

The current study presents the synergy of six different surveying techniques for the multidisciplinary mapping and monitoring of an active landslide in Western Greece. The analyzed landslide is quite challenging because it has affected a small village destroyed houses and roads and put human lives in danger. The geology of the broad area is relatively simple and the landslide was triggered by heavy rainfalls during two successive rainfall periods. It has occurred into a village destroying two houses and the main road and the landslide deserved high attention by the local authorities enabling the installation of inclinometers as the rest of the village could be in danger. The landslide was triggered in 2014 and reactivated during 2015. During the period between the first and the second sliding events, the slope was moderately modified and thus the entire period of sliding can be studied. The final aim of this paper is to highlight and validate a methodology for landslide analysis based on multiple sensors data integration, useful to obtain a comprehensive Geographic Information System (GIS) which can successfully be used to improve the knowledge of a specific landslide phenomenon in order to prevent and mitigate the risk. Photogrammetric and interferometric processing has been applied to a complex set of remote sensing data used in this study, such as high resolution satellite images, digital airphotos, aerial photos acquired from a UAV and radar data. GNSS measurements and continuous inclinometer measurements are being performed. The multifunctional technology of GIS is used in order to collect, storage, manage, process, analyze and cartographically represent the previously described complex geoscientific information. The remainder of the current paper is structured as follows: In the following section, the study area and the landslide history are described. In the third section, the equipment, the available data and the methodology are presented. In the fourth section, an analysis of the six surveys and their results are presented. In the fifth section, the integration of the individual results is exposed and discussed and finally in the last section the conclusions are presented.

Study area and landslide history

Study area

The landslide occurred in the Analipsi village located in Western Peloponnesse (see Figure 1). The broader area consists of a complex structural regime due to an array of active normal and strike-slip faults that dissect the broader study area (Zygouri; Koukouvelas, Kokkalas, Xypolias, & Papadopoulos, 2015). These faults are trending of NW- and NNE- to NE controlling the deposition of sediments in the so-called Elis basin (Hageman, 1977; Kamperis, Ioakim, Tsaila-Monopol, & Tsapralis, 1992; Koukouvelas, Mpresiakas, Sokos, & Doutsos, 1996). The Elis basin is accumulating post-Miocene clastic sediments of more than 1700 m in thickness (IGME 1979; Kelletat, Kowalczcyk, Schroder, & Winter, 1976). In more detail, the oldest exposed sediments in Elis basin are fine-grained sediments with intercalations of sands of Pliocene to Pleistocene age, accumulated in marine or lagoonal to tidal flat sedimentary environments (Danatsas & Strauch, 1994; Hageman, 1977; Kamperis et al., 1992). During the Holocene, the Elis basin accumulated fluvial deposits, mainly sands and gravels, from the Peneus and other smaller rivers (Kontopoulos & Koutsios, 2010; Kraft, Rapp, Gifford, & Aschenbrenner, 2005). Sedimentological analysis in the area around the Analipsi village suggests the occurrence of lagoonal to marine sandy
clays of late Pliocene age. From a geomorphological point of view, the wider study area is interpreted as a large and deeply dissected fluvial to marine terrace. This terrace further north is of post-Tyrrhenian age characterized by sedimentation rate as high as 0.2 mm/year, while the region was uplifted at a rather stable rate of 0.6 mm/year over the same period (Zygouri et al., 2015 and references therein). In terms of the orientations of the main streams draining the study area, these resemble the drainage pattern that is characteristic for the entire NW Peloponnesian classified as transverse or longitudinal to the N–S trending structural grain of the Alpine basement (Zygouri et al., 2015). Local geology consists of the “Vounargo formation”, weathered sandy materials and landslide materials (Institute of Geological and Mineral Exploration, 1979). The Analipsi village is founded on the “Vounargo formation” which consists of irregular alterations of banks of finely to medium-grained brittle sandstones with interpolation of sandy and clayey marls. The landslide materials consist of loose sandy soils that have been slided over the underlying sandy-silt marls of the “Vounargo formation”.

**Landslide history**

The area comprises an extensive instability zone of periodically triggered landslide events and intervals of creep. The first significant failure in Analipsi has been recorded in March 2014 as a result of the intense and prolonged rainfall that constitutes the main triggering factor for the landslide initiation in the surrounding area (Koukis, Sabatakakis, Lainas, Depountis, & Skias, 2010; Lainas, Sabatakakis, & Koukis, 2016; Sabatakakis, Koukis, & Mourtas, 2005). The main failure was a translational multiple slide involving recent soil and Neogene sediments. The main scarp was located at the western edge of the village affecting a newly constructed house that was partially destroyed by sliding masses. Its vertical movement was about 4 m and its head width was about 70 m, while successive minor scarps with vertical movement up to 2.8 m at its right flank were produced within the landslide zone in the cultivated fields (see Figure 2). The total length of landslide zone

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**Figure 1.** Location map of the study area (left) and a WorldView-2 satellite image (right) showing the Analipsi village.

**Figure 2.** Photographs taken after the first landslide activation in March 2014. The top photograph shows the head scarp of the landslide. The bottom one shows the right flank of the landslide.
was about 300 m. Just 1 month later (April 2014), further ruptures occurred in the upper and lateral part of the slide (see Figure 3).

In March 2015, the slide was once again reacti-vated at its crown area during intense and prolonged rainfall. The pavement of the main road failed into a zone of about 85 m, representing the new crown, the total length of the slide increased by almost 50 m southeastward and two houses were totally destroyed (see Figure 4). From hereinafter and onward, the entire slide formed during 2014 and 2015 will be called as the Analipsi slide.

The Analipsi slide generally consists of a slow and short-moving landslide, while the periodically induced landsliding phenomena can be generally classified as rapid and short moving (Sassa, 2004) with values of average apparent friction over 1.0.

The local geology as it is surmised by the in situ investigation and mapping combined with exploratory boreholes, involves the Plio–Pleistocene sediments mainly consisting of brownish yellow, stiff, sandy–silty marls with intercalations of medium dense, silty sands and weak, fine-grained, marly sandstones of upper horizon, as well as the dark gray, very stiff, clayey marls of the lower one. The upper part of the marly formation formed a weathered zone of several meters of thickness, including clays of low plasticity marls with water content very close to the plastic limit and clayey sands. Many fissures and some discontinuities which were also developed into the weathered zone of the formation, due to previous tectonic action and nonuniform volume changes that follow chemical weathering, had resulted in reducing the overall strength of the weathered marls. The weathered zone was generally mixed with landslipped recent materials including sand and some gravel and over a large area they constitute a unique semi permeable mantle covering the Plio–Pleistocene sediments. The rupture surface was at a depth not exceeding 7 m involving recent materials and weathered mantle through the contact zone with clayey, very stiff and impermeable gray-colored marls. Ground water level in the weathered mantle reached the slope surface during the heavy rainfall resulted to the pore pressure built-up.
Equipment, datasets and methodology

Equipment

All the equipment used in the current study is presented in Figure 5 and analytically presented in the following subsections.

Unmanned aerial vehicles

The flight campaigns over the landslide area were performed in different dates, one with an off-the-shelf DJI Phantom 3 Advanced (see Figure 5(f)) and one with a custom-made UAV. The custom-made UAV that was used for this study (see Figure 5(g)) is a hexacopter that bears two camera gimbals. It has a stabilizer (see Figure 5(h)) in order to absorb all the distortions. The gimbals (see Figure 5(k)) allow the simultaneous capture of vertical scenes and oblique scenes to realize different aspects of the same area. The cameras that the gimbals bear are two GoPro Hero 3+ Black Edition action cameras. The RGB GoPro cameras are capable of capturing photographs at 12MP (3000 × 4000 pixels), have a focal length of 2.77 mm and their pixel pitch is 1.55 µm. In addition to the gimbals, the UAV is also equipped with a GNSS module that allows automatic flights and is powered by two batteries that offer a total flight time of about 15 min. Having this flight autonomy, the specific UAV can cover areas of 0.16 km$^2$ in a single pass (Nikolakopoulos, Koukouvelas, Argyropoulos, & Megalooikonomou, 2015b). Its positioning accuracy is 2.5 m horizontally and 0.8 m vertically.

Topographic equipment and Global Navigation Satellite System

The topographic survey and ground control points (GCPs) collection were performed using a Leica TCR1102 tachymeter (see Figure 5(b)) and two GNSS sensors: a Trimble R8 5800 geodetic GNSS (see Figure 5(a)) and a Leica GS08 Plus receiver (see Figure 5(g)). Both receivers were used without a dedicated base station, but with differential position corrections from the Hellenic Positioning System – through GSM network- and Real-Time Kinematic. The receivers are capable of GPS (L1, L2 and L2C frequencies), GLONASS (L1 and L2 frequencies) and satellite-based augmentation systems (WAAS, GAGAN, MSAS and EGNOS systems). The accuracy specifications for this receiver are 10 mm + 1 ppm horizontally and 20 mm + 1 ppm vertically. During the GCPs’ measurements, the horizontal Root Mean Square Error (RMSE) was between the values 0.9 and 1.3 cm, whereas the vertical RMSE between the values 1.4 and 1.9 cm.

Regarding the differential position corrections, the Hellenic Positioning System is composed of 98 base stations. Except for the physical base stations, the
network is further densified using Virtual Reference Stations – a technique that also allows for post-processing and the Master Auxiliary Concept technique. The mean distance between stations fluctuates at 50–70 km.

**Persistent scatterers**

As already noted, PSI is an ideal technique for monitoring Earth’s surface as it is able to measure microscale displacements in terrain surface. The approach could exploit artificial corner reflectors for the validation of ground deformation due to their stability and high signal-to-noise ratio. More specifically, corner reflectors are retro-reflectors consisting of perpendicularly intersecting flat surfaces and they are mainly made of metal. The basic principle of the operation of corner reflectors is the generation of a strong radar echo from objects that would normally have low detectability. Thus, these reflectors are designed to reflect the microwave radio waves transmitted by radar systems, exactly back toward the radar antenna indicating a strong return to the system screen. That very strong backscatter contributes in good interferometric phases to derive the deformation estimate, while at the same time it is possible to detect the deformation measurement points. In the particular survey, the persistent scatterers (corner reflectors) were designed and constructed at the University of Patras (see Figure 5(i)). They are made of aluminium lamina and consist of several assembled parts for easy transportation and assembling.

**Boreholes and inclinometer**

After the third landslide event, three exploratory boreholes up to 20 m deep were drilled (see Figure 5(d)) in order to identify the subsurface geology, samples were retrieved for laboratory tests and two of them were equipped with inclinometer casing while the third one with a piezometer casing. Borehole (G1) was drilled in the landslide zone while borehole (G3) was drilled outside the landslide zone, few meters above the landslide crown. In the same period, the GNNS network was installed for the measurement of surface displacements.

The technical equipment in a complete inclinometer system includes (a) the cable reel, (b) the inclinometer probe, containing two microsensors (Microelectromechanical Systems), (c) the logger and (d) a cable gate (see Figure 5(e)). These sensors succeed highly accurate and repeatable readings of ground deflections. Probes that contain two perpendicular accelerometers are called biaxial probes, so only two passes of the probe are required, along the borehole casing, to measure movement in the four different directions (Stark & Choi, 2008).

**Datasets and methodology**

Different spatial datasets consisting from both raster and vector layers were implemented in a GIS database and processed during the different stages of the survey. The base dataset consists of an orthomosaic and a DSM created for the needs of the Greek Cadastre. The orthomosaic was developed with photogrammetric techniques from digital aerial photographs acquired between the years 2007 and 2009. It covers the whole country and has a spatial resolution of 0.50 m. The respective DSM created from the same imagery has a 5 m × 5 m pixel size and a nominal vertical accuracy better than 2 m. The orthomosaics and DSMs were created by the National Greek Cadastre and Mapping Agency and there was no need for further processing. Both the orthomosaic and the DSM are the most accurate official datasets available in Greece and they were used as base maps for the whole study.

Digital photos from the UAVs flight campaigns were processed and orthophotos and DSMs were created using Agisoft PhotoScan Professional software. According to previous studies (Nikolakopoulos, Soura, Koukouvelas, & Argyropoulos, 2016), the horizontal accuracy of the UAV orthophotos reach 99% of the respective accuracy of a topographic survey while the vertical accuracy is better than 0.2 m.

A WorldView-2 image acquired on 21 March 2015 just a week after the third landslide has been processed using Leica Photogrammetry Suite and another orthophoto was developed.

Additional several Sentinel-1 radar images were obtained and processed by the freely available SNAP software, aiming at the generation of interferometric DSMs and ground deformation monitoring through PSI technique.

The inclinometer measurements and the vector data from the GNSS campaigns and from the topographic surveys were also processed in GIS environment.

All the previously mentioned datasets were processed using different techniques described in more details in the following sections. The flowchart of the methodology followed in this study is presented in Figure 6.

**Surveys and results**

**Topographic surveys**

The first topographic survey took place after the last landslide event on 15 March 2015. During this topographic survey, a geodesic network of control points
was installed inside – along the main axis of instability – and outside the landslide mass for a precise monitoring of the movements (see Figure 7). The points were all measured with the Trimble R8 5800 GNSS Receiver. In order to check the accuracy of the measurements, two triangulation points that were close to the Analipsi village, and which are part of a national triangulation network with up to fourth-order triangulation points scattered around the country, were available and their 3D coordinates were already known to a high precision. These triangulation points were at a distance of about 1 km – in separate directions – around the Analipsi village and they could provide an accurate representation of the expected measurement errors. So, after the measurements of the geodesic network were performed, the two triangulation points were measured with the same settings.

In addition to the geodesic network, almost every building in the village (see Figure 5(c)) was measured in order to perform a stability validation of the landslide and create a base from which we could monitor movements of the buildings and hence perform some sort of network densification.

The next topographic survey was performed on 15 July 2016. All the aforementioned control points were measured again and the results showed that there was no further movement to the buildings out of the Analipsi slide crown. Based on the topographic survey, the landslide seemed that had been stabilized sometime before 15 July 2016.

Figure 6. The flowchart of the multidisciplinary survey.

Figure 7. The topographic survey map showing the main triangulation points, the ground control points, the main cracks of 2014, the main road and the buildings in close proximity to the landslide crown area.
**GNSS campaigns**

The GNSS campaigns can be divided in two different actions. Massive measurements were performed after every landslide event in order to map the main cracks. Repeated measurements (Table 1) of selected GCPs (see Figure 8) in and out of the instability zone in order to monitor the activity of the landslide were also performed during the field campaigns.

A few thousands of GNSS measurements (see Figure 8) were combined with an existing very accurate DSM in order to simulate the mass movement and the results are presented in Figure 9. The existing cadastre DSM that was representing the morphology of the village before the landslide was enriched with points (collected in April 2014) representing the morphology of the area after the first ground movement. In details, almost 5000 points collected with differential GNSS were implemented in the preexisting DSM using the “create surface” toolbox in ERDAS IMAGINE software. A new DSM was generated incorporating the occurred changes to the relief. Then in ARCGIS software, the “cut/fill” command was used in order to automatically detect the changes to the two DSMs. When the “cut/fill” operation is performed, by default a specialized renderer is applied to the layer that highlights the locations of cut and of fill. The determinant is in the attribute table of the output raster, which considers positive volume to be where material was cut (removed), and negative volume where material was filled (added). In the specific landslide area, the “cut” zones correspond to the depletion while the “fill” zones correspond to the accumulation.

As shown in Figure 9, relief changes are observed including zones of depletion (blue colored areas) and zones of accumulation (red colored areas). The unaffected (stable) areas are represented with gray color.

The continuous measurements of the GCPs with the GNSS receivers lead to the conclusion that after the end of April 2015, the landslide has been stabilized.

### Table 1. The dates of the GNSS campaign.

| GNSS campaign | Date       | Event/fieldwork                                      |
|---------------|------------|-----------------------------------------------------|
| First         | 20 March 2014 | Mapping after the first landslide event               |
| Second        | 02 April 2014 | Mapping after the second landslide event              |
| Third         | 11 February 2015 | Mapping after the landslide reactivation             |
| Fourth        | 14 March 2015 | Mapping after the third (major) landslide event/boreholes drilling |
| Fifth         | 25 April 2015 | First UAV campaign                                   |
| Sixth         | 17 May 2015 | Second UAV campaign                                  |
| Seventh       | 14 July 2015 | Third UAV campaign/deployment of scatterers          |
| Eighth        | 21 March 2016 | Fourth UAV campaign                                  |
| Ninth         | 28 April 2016 | Fifth UAV campaign                                   |
| Tenth         | 15 July 2016 |                                                      |

**High resolution satellite data processing**

As described earlier, change detection technique presupposes the existence of two (pre-event and post-event) images for the landslide area with a quite similar spatial resolution. In the current study, the orthoimage of the Greek Cadastre is used as pre-event image. A week after the third landslide, WorldView-2 satellite acquired a bundle image (post-event image) covering the study area. A panchromatic band with 0.4 m spatial resolution and eight multispectral bands with a spatial resolution of 1.6 m were fused based using the Hyperspherical Color Space algorithm. The specific algorithm was developed for ameliorating the spatial resolution of WorldView-2 multispectral data (Padwick, Deskevich, Pacifici, & Smallwood, 2010). According
to the developers, the image processing chain of the specific algorithm includes three steps: circuitry for converting the multispectral image into a hyperspherical color space, matching the intensities of the multispectral image to the intensities of the corresponding panchromatic image and then retransforming the color space back to the original multispectral image. The intensity matching of the present invention includes modification of the intensities of the multispectral images based on dynamically generated statistical models and a selected sharpening parameter $\beta$. The specific algorithm was tested among others and provided excellent results in neighboring areas in Western Greece (Vaiopoulos & Nikolakopoulos, 2015) and thus it is used in the current study.

The new multispectral image was orthorectified using Leica Photogrammetry Suite. The orthophoto and the DSM of the Greek Cadastre were used as reference for the collection of 30 GCPs. Those points had a good dispersion – meaning that the choice of the GCPs was made by trying to evenly distribute them in the whole image while an emphasis was given on the Analipsi village area. The aerial triangulation process estimated the RMSE values for the block and it was less than half pixel. This value is considered satisfying to continue with the orthorectification of the satellite image. The WorldView orthoimage was overlaid to the orthophoto of the Greek Cadastre and the damages to the buildings and the main road were digitized (see Figure 10).

As a result of the satellite image processing, the house at the southwest end of the landslide has been shifted 3.1 m in the horizontal axis in a direction of 289°, while the second one has been shifted 1.6 m in 317° direction. The crack on the road has a width of 2–4 m and a depth of about 4 m (measured in the field).

**UAV data**

Five different UAV flight campaigns were carried out in different time periods within 1 year. The exact dates of the flight campaigns as well as the number of photographs acquired by each one are presented in Table 2.

The images acquired from the Gopro cameras during the hexacopter flights were processed in order to remove the lens distortion effect. The elimination of the distortion is achieved using the Adobe Lightroom software that incorporates a lens
distortion removal feature and also the lens profiles for the specific cameras. The distortion removal process rearranges the pixels of the image to create corrected images. Though the pixels are rearranged and some cropping is performed, the parallax of the images is not lost, so they can be used to create 3D models. The general geometric distortion model that is used by Adobe Lightroom for fish-eye lenses is analytically described in Chen, Jin, Chien, and Chan (2010). More details and figures about the lens distortion removal procedure are presented in Nikolakopoulos et al. (2016).

After the lens correction, the datasets from the repeated UAV campaigns were imported in Agisoft Photoscan software. As described in detail in a previous study (Skarlatos, Procopiou, Stavrou, & Gregoriou, 2013), the software employs computer vision techniques along with photogrammetric analysis to perform direct georeferencing or bundle adjustment with GCPs or simple similarity transformation over the whole block without GCPs. As more images are added to the block, more points are taken into consideration and ensure the internal block geometry.

Table 2. The dates of the UAV flight campaigns and the number of the acquired photographs.

| Flight campaign        | Date         | No. of photographs |
|------------------------|--------------|--------------------|
| First (Hexacopter)     | 17 May 2015  | 431                |
| Second (Hexacopter)    | 14 July 2015 | 628                |
| Third (Phantom)        | 21 March 2016| 136                |
| Fourth (Phantom)       | 28 April 2016| 363                |
| Fifth (Hexacopter and Phantom) | 15 July 2016 | 678                |

Figure 10. At the top: Comparison between the WorldView-2 images and the orthophoto of the Greek Cadastre. At the bottom: Mapping the damages a week after the third landslide from the WorldView orthoimage. With black color the initial position of the buildings (mapped from the cadastre image) is represented. The red color represents the house allocations after the landslide. The major scarp and cracks were also mapped (red dots).
In order to achieve the higher possible accuracy of the models, many artificial targets that could be used as GCPs were scattered in the village. The coordinates and height of each of these targets were measured using a high-accuracy geodetic GNSS receiver in order to ensure accurate positioning in Greece’s Coordinate System (also known as EGSA 1987 or EPSG 2100).

This software creates first a sparse point cloud that is followed by the creation of depth maps and a dense point cloud. The next step is the creation of a mesh and then a texture for the model. Using the aforementioned GCPs, the model is georeferenced in the three dimensions in order to create orthophotos and DSMs. The orthomosaics that were created offer a ground spatial resolution of 2 cm and their respective DSMs a resolution of 4 cm (see Figure 11).

The UAV-derived orthophotos were used in order to map the damages and to monitor the landslide evolution. As it can be observed in Figure 12, the orthophotos were used in order to map the evolution of the landslide crown area and its impact on the

![Figure 11. At the left: Orthophotos from the different UAV campaigns. At the right: The respective DSMs.](image)

![Figure 12. Mapping the changes to the road and monitoring the building movements at the southwest end of the landslide during the different UAV campaigns. With black color the initial position of the building (mapped from the cadastre image) is represented. The green color represents the house allocation during the first flight (17 May 2015), while the red color represents the building position as it was mapped from the third UAV orthophoto (21 March 2016). The crack on the road is enlarged between the two dates.](image)
road network and the buildings of the Analipsi village (see Figure 12). The red color represents the road as it was mapped during the third UAV flight (21 March 2016) while the green color represents the road during the first flight (17 May 2015). From these two flight campaigns, it is evident that the crown of the landslide is moving southward causing the collapse of another part of the village main road. This result suggests that the main scarp of the Analipsi slide remained active for almost a year after the inferred slide stabilization by the GNSS campaigns and inclinometers data. Thus, it is extracted that the evolution of the main scarp is a matter of gravitational collapse. The same colors determine the position of the destroyed house during the different flights. In Figure 12, with black color the initial position of the building (mapped from the cadastre image) is represented. The red color represents the building position as it was mapped from the third UAV orthophoto while the green color represents the house allocation during the first flight (17 May 2015).

The UAV flights over the area continued every 3 months. The last campaigns results proved that there is no further movement to the buildings of the village or to the crown of the slide.

Interferometry

Radar image processing focuses on two different issues: the first one is the detection of the relief changes caused by the third landslide event, and the second one is the continuous monitoring of the landslide using persistent scatterers.

The first issue, i.e. the detection of the relief changes, was based on the creation of two DSMs, one utilizing data before the landslide and another one using data after the event, and the subsequent comparison of them. In particular, 11 Interferometric Wide Swath Mode images from Sentinel-1 mission were acquired since October 2014 until March 2015 for DSM extraction before the occurrence of the landslide. Additionally, 10 respective images following the landslide, from March 2015 until May 2015 were subjected to interferometric process yielding a second DSM (Kyriou & Nikolakopoulos, 2016). Elevation profiles perpendicular to the crown of the landslide were created (see Figure 13) and there are height differences before and after the landslide. The elevation profiles and the height differences were calculated using the ERDAS Imagine software and more especially the spatial profile algorithm. The results revealed that the elevation changes on the crown of the landslide were perceived. The elevation difference in some specific points rises at 5 m (Kyriou & Nikolakopoulos, 2016), something which is in agreement with the field data measurements, demonstrating that the method works correctly.

Concerning the continuous monitoring of the landslide using persistent scatterers, the approach is based on the exploitation of large stacks of satellites Synthetic Aperture Radar (SAR) images in order to determine the behavior of the landslide, identify ground motions and to investigate the triggering factors. In more detail, PSI requires large stacks of SAR images, acquired over the same area, in order to generate several single-pair interferograms reference to a master image with the objective to track the displacement history of corner reflectors. It is worth mentioning that each measurement is referred temporally to a unique reference image for the minimization of the effects of spatial and temporal baselines and for the maximizing of the overall

Figure 13. At the top: The no. 1 elevation profile before the landslide from Sentinel-1 images. At the bottom: The no. 1 elevation profile after the landslide from Sentinel-1 images. There are height differences between the two profiles.
coherence of the interferometric stack, as well as the greater the number of available scenes the better the quality of the deformation. PSI technique utilizing Sentinel-1 data leads to satisfactory results since it exploits temporally consecutive interferograms with high coherence due to the short revisiting cycle of these data as well as the ability of such data to reduce the importance of the so-called residual topographic phase component. In the context of extraction reliable and highly accurate results, the specific survey is in the process. Corner reflectors are deployed in the landslide area (see Figure 5(c)) and the processing has already started. The first step was to confirm the visibility of the artificial permanent scatterers in the SAR images. In particular, multiple images before and after the installation of each reflector were obtained. On the later images, a strong signal return occurred at installation’s location, which was imprinted with high reflectance values in Sentinel-1 images. Thereafter, the corner reflector’s visibility was tested in both ascending and descending passes. The orientation of corner reflector is responsible for the fact that it is visible in the ascending pass of Sentinel-1 mission, while during the descending one it is hard to be detected (see Figure 14). The collection and the processing of large stacks of SAR images covering the area of Analipsi continues.

**Inclinometer data processing**

The inclinometer measurements started on 18 March 2015, by taking the initial readings. The deformation measurements were carried out by inserting the inclinometer probe along the A axis of the casing that had been placed into the borehole, while for the B axis automatic calculations were performed. The probe was passed along the casing to measure its inclination, with respect to vertical, or 45° or horizontal, at 500 mm intervals. It is important to mention that measurements were made at approximately monthly interval. In particular, the measurements were carried out during a period of 15 months.

Figure 15 shows the inclinometer cumulative displacement profiles along the main axis of the landslide, measured in boreholes G1 and G3. From inclinometer G1, outside the landslide zone, there is no evidence of movement, while from inclinometer G3, inside the landslide zone a potential displacement is appeared at a depth of 6–7 m. The monthly measurements proved that the slide has been stabilized sometime in October 2015. The depth of measured displacements corresponds to the potential failure surface found from the sampling as well as the geotechnical laboratory program carried out in borehole G3. The failure surface is a low shear strength zone intercepting the underlying clayey marls and the overlying sandy–silty marls of the Neogene formations. It seems that the landslide has been stabilized the last few months due to the absence of intense and prolonged rainfalls. Rainfall seems to be the main trigger mechanism of the landslide, as rainfall causes ground water lever to rise above the low shear strength intersection zone, lying among the clayey

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**Figure 14.** The possibility to detect the artificial persistent scatterer in different Sentinel-1 images is presented in both ascending and descending passes.
and the sandy–silty marls. However, a long-term survey is required for understanding the kinematics in detail.

**Discussion and conclusions**

Landslides, due to their complex kinematics and their usual location over large and inaccessible areas, call for the need of different methods and techniques to measure surface modifications caused by large earthflow in order to understand their dynamics and to detect early indicators of future rapid movements (Angeli, Pasuto, & Silvano, 2000; Giordan et al., 2013). The evolution of the landslide in depth can be easily monitored using the very accurate technology of the inclinometers. Surface slide monitoring can be carried out by using different types of terrestrial or remote sensing instruments. Barbarella and Fiani (2013) claimed that the most accurate results are given by Total Stations and by GNSS receivers. But with these methods, one can survey the position of few points which should be however well dispersed. All the aforementioned methods cannot be applied in inaccessible and steep areas. Remote

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**Figure 15.** Inclinometer cumulative displacement profiles along the main axis of the landslide as measured in the G1 and G3 boreholes.
sensing methods provide two distinct solutions for landslide monitoring: optical and radar data processing. In the first case, the very high resolution data of the newer satellites such as QuickBird, GeoEye, WorldView-2 can cover large or isolated areas with acceptable accuracies for landslide damage mapping. Nichol et al. (2006) proved that IKONOS stereo images overpass the requirements of landslide hazard assessment when the scale of observations is between 10 and 100 m and where microscale features to be identified have dimensions of 1–10 m. The major drawbacks are the high cost of data acquisition that makes the repeated monitoring impossible and the dependence to the weather conditions. Interferometry using radar data overpasses the obstacles of weather conditions and costs but it requires specialized software and large time series. The brand new technology of UAVs could provide an affordable solution for repeated campaigns even in steep terrains for the purposes of monitoring a landslide. The accuracy of this method even promising is still under investigation, but the repeated UAV campaigns probably overcome accessibility problems for landscape changes monitoring.

As described in the “Introduction” section, the current study presents for the first time the synergistic use of six multidisciplinary surveys for the mapping and monitoring of an active landslide. Each independent survey has provided results in landslide damage mapping and/or continuous landslide monitoring. The existence of different kinds of spatial information, raster data and vector data, point polygons and polylines, measurements in excel, etc. necessitated the use of a GIS software for the implementation, harmonization and integration of the results. First, the usefulness of the GIS is very clearly presented in the case of the GNSS survey. Existent DSM (raster data) was enhanced with vector data (GNSS point measurements) and automatic algorithms were used for the creation of depletion and accumulation zones. Furthermore, the different measurements from the topographic and the GNSS campaigns, the satellite and the UAV image processing as well as the inclinometer survey are integrated (see Figure 16) in GIS and finally the direction and the velocity of the land movement are determined. Furthermore, GIS is very crucial in producing easily understandable maps for decision makers and local authorities. As it can be observed in Figure 16, the direction of the slide is West–North West. The exact direction is extracted from both the inclinometers data processing (borehole G3) and the remote sensing data processing (house displacements). This result is in absolute harmony with the observed scarps that were mapped in the fields just after the events (see Figure 16). The upper part of the landslide is stabilized as extracted from both the GNSS measurements and the inclinometer measurements (Borehole G1).

Multidisciplinary surveys allow understanding the processes at depth and landscape changes at the surface. In addition, the proposed methodology excludes the misinterpretation between gravitational collapse in the crest areas with true landslip movements at depth. As described in a similar study (Castagnetti et al., 2013), the reliability and the

![Figure 16](image-url). Synthetic map of the Analipsi landslide that incorporates the measurements from the diverse surveys.
integration of results in a common reference framework within a GIS play a key role when public administrations have to use monitoring networks to plan actions in case of emergency.

Actually results from the Analipsi village showed that the landslide seems to have been stabilized within a few months after its rejuvenation during the 2015 rain period. Both the findings from the subsurface monitoring with the inclinometer instrumentation and the findings from the surface survey (GNSS measurements, topographic measurements, UAVs campaigns) converge to the same result. In the future, all the surveys will be continued and the results will be enriched with the PSI measurements.

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References

Akca, D. (2013). Photogrammetric monitoring of an artificially generated shallow landslide. The Photogrammetric Record, 28, 178–195.

Angeli, M.G., Pasuto, A., & Silvano, S. (2000). A critical review of landslide monitoring experiences. Engineering Geology, 55, 133–147.

Barbarella, M., & Fiani, M. (2013). Monitoring of large landslides by terrestrial laser scanning techniques: Field data collection and processing. European Journal of Remote Sensing, 46, 126–151. doi:10.5721/EurJRS20134608

Barbarella, M., Fiani, M., & Lugli, A. (2015). Landslide monitoring using multitemporal terrestrial laser scanning for ground displacement analysis. Geomatics, Natural Hazards and Risk, 6(5–7), 398–418. doi:10.1080/19475705.2013.863808

Baum, R.L., Messerich, J., & Fleming, R.W. (1998). Surface deformation as a guide to kinematics and three-dimensional shape of slow-moving, clay-rich landslides, Honolulu, Hawaii. Environmental and Engineering Geoscience, 4(3), 283–306.

Bianchini, S., Cigna, F., Del Ventisette, C., Moretti, S., & Casagli, N. (2013). Monitoring landslide-induced displacements with terraSAR-X persistent scatterer interferometry (PSI): Gimigliano case study in Calabria region (Italy). International Journal of Geosciences, 4, 1467–1482.

Bovenga, F., Refice, A., Pasquariello, G., Nitti, D.O., & Nutricato, R. (2014). Corner reflectors and multi-temporal SAR interferometry for landslide monitoring. Proceedings of SPIE, 9243, 92430I-1–92430I-10.

Calcaterra, S., Cesi, C., Di Maio, C., Gambino, P., Merli, K., Vallario, M., & Vassall, R. (2012). Surface displacements of two landslides evaluated by GPS and inclinometer systems: A case study in Southern Apennines, Italy. Natural Hazards, 61(1), 257–266. doi:10.1007/s11069-010-9633-3

Cascini, L., Calvello, M., & Grimaldi, G.M. (2014). Displacement trends of slow-moving landslides: Classification and forecasting. Journal of Mountain Science, 11(3), 592–606. doi:10.1007/s11629-013-2961-5

Castagnetti, C., Bertacchini, E., Corsini, A., & Capra, A. (2013). Multi-sensors integrated system for landslide monitoring: Critical issues in system setup and data management. European Journal of Remote Sensing, 46, 104–124. doi:10.5721/EurJRS20134607

Castagnetti, C., Bertacchini, E., & Rivola, R. (2014). A reliable methodology for monitoring unstable slopes: The multi-platform and multi-sensor approach. Proceedings of SPIE, 9245, Earth Resources and Environmental Remote Sensing/GIS Applications V, 92450J, doi:10.1117/12.2067407

Chandler, J.H. (2001). Terrain measurement using automated digital photogrammetry. In: Griffiths, J.S. (Ed.), Land Surface Evaluation for Engineering Practice, Geological Society of London, 18, 13–18.

Chen, S., Jin, H., Chien, J., & Chan, E. (2010). Adobe camera model. Technical Report, Adobe Systems Inc.

Colesanti, C., & Wasowski, J. (2006). Investigating landslides with space-borne Synthetic Aperture Radar (SAR) interferometry. Engineering Geology, 88, 173–199.

Corsini, A., Borgatti, L., Coren, F., & Vellicco, M. (2007). Use of multitemporal airborne lidar surveys to analyse post-failure behaviour of earth slides. Canadian Journal of Remote Sensing, 33(1–4), 116–120.

Crosetto, M., Gili, J.A., Monserrat, O., Cuevas-Gonzalez, M., Corominas, J., & Serral, D. (2013). Interferometric SAR monitoring of the Vallecibre landslide (Spain) using corner reflector. Natural Hazards Earth System Sciences, 13, 923–933.

Crosetto, M., Monserrat, O., Cuevas-González, M., Devanthéry, N., & Crippa, B. (2016). Persistent scatterer interferometry: A review ISPRS. Journal of Photogrammetry and Remote Sensing, 115, 78–89. doi:10.1016/j.isprsjprs.2015.10.011

Čyžiené, J., Minkevičius, V., Mikulénas, V., & Satkūnas, J. (2012). Results of persistent scatterer interferometry of the new planned visaginas nuclear power plant area, Lithuania. Geologia, 54(4(S0)), 136–154.

Danatas, I., & Strauch, F. (1994). Die bedeutung plio-pleistozäner ostrakoden der NW Peloponnes (Griechenland). Münstersche Forschungen zur Geologie und Paläontologie, 76, 169–190.

Del Ventisette, C., Righini, G., Moretti, S., & Casagli, N. (2014). Multitemporal landslides inventory map updating using spaceborne SAR analysis. International Journal of Applied Earth Observation and Geoinformation, 30(1), 238–246. doi:10.1016/j.jag.2014.02.008

Di Maio, C., Vassallo, R., Vallario, M., Calcaterra, S., & Gambino, P. (2013). Surface and deep displacements evaluated by GPS and inclinometers in a clayey slope. C. Margotti et al. (eds.), Landslide Science and Practice, 2, Springer-Verlag Berlin Heidelberg. doi:10.1007/978-3-642-31445-2_34

Fabijs, M., Menin, A., & Achill, V. (2011). Landslide displacement estimation by archival digital photogrammetry. Italian Journal of Remote Sensing, 43, 23–30. doi:10.5721/IJRS20114322

Fiorucci, F., Cardinali, M., Carlà, R., Rossi, M., Mondini, A. C., Santurri, L., ... Guzzetti, F. (2011). Seasonal landslides mapping and estimation of landslide mobilization...
rates using aerial and satellite images. *Geomorphology*. doi:10.1016/j.geomorph.2011.01.013

Gens, R., & Van Genderen, J.L. (1996). SAR interferometry—Issues, techniques, applications. *International Journal of Remote Sensing*, 17, 1803–1835.

Giordam Daniele, D., Allasia, P., Manconi, A., Baldo, M., Michele Santangelo, M., Cardinali, P., ... Guzzetti, F. (2013). Morphological and kinematic evolution of a large earthflow: The Montaguto landslide, southern Italy. *Geomorphology*, 187, 61–79.

Hageman, J. (1977). Stratigraphy and sedimentary history of the upper cenozoic of the pyrgos-area (Western-Peloponnesus), Greece. *Anna Geol Pays Hellenique*, 28, 299–333.

Institute of Geological and Mineral Exploration, Geological map of Greece, 1:50,000, Sheet Amaliada, Athens, Greece, (1979)

Kääb, A. (2000). Photogrammetry for early recognition of high mountain hazards: New techniques and applications. *Physics and Chemistry of the Earth, Part B*, 25(9), 765–770.

Kamperis, E., Ioakim, C., Tsiala-Monopoli, S., & Tsapralis, V. (1992). Geodynamic and palaeogeographic evolution of Western Peloponnesus (Greece) during the Neogene. *Paleontologia i evolució*, 24–25, 363–376.

Kavoura, K., Sabatakakis, N., & Tsiambaos, G. (2016). Long term ground displacements due to a large landslide in western Greece. In Aversa, Cascini L., Picarelli L. and Scavia C. (Eds.), *Landslides and engineered slopes. Experience, theory and practice* (1177–1181). CRC Press. doi:10.1201/b21520-142

Kelletat, D., Kowalczyk, G., Schroder, B., & Winter, K.P. (1976). A synoptic view on the neotectonic development of Peloponnesian coastal regions. *Zeitschrift der Deutschen Geologischen Gesellschaft*, 127, 447–465.

Kontopoulos, N., & Koutsios, A. (2010). A late holocene record of environmental changes from Kotithi lagoon, Elis, Northwest Peloponnesus, Greece. *Quaternary International*, 225, 191–198.

Koukis, G., Sabatakakis, N., Lainas, S., Depountis, N., & Skias, S. (2010). Engineering geological investigation of heavy rainfall induced landslides in wildfire affected areas, western Greece. In Williams, et al., (Eds.), *Geologically Active. Proceedings of the 11th IAEG Congress* (pp. 331–338). Auckland, CRC Press, New Zealand.

Koukouvelas, I.K., Mpresiakas, A., Sokos, E., & Doutous, T. (1996). The tectonic setting and ground hazards of the 1993 Pyrgos earthquake, Peloponese, Greece. *Journal of the Geological Society*, 153, 39–49.

Kraft, J.C., Rapp, G., Gifford, J.A., & Aschenbrenner, S.E. (2005). Coastal change and archaeological settings in Elis. *The American School of Classical Studies at Athens. Hesperia*, 74, 1–39.

Kyriou, A.S., & Nikolakopoulos, K.G. (2016). Sentinel-1 data for the detection and mapping of landslides. A case study from Western Peloponese, Greece. In Ouwehand L. (Ed), *Proceedings of ‘Living Planet Symposium 2016’, Prague, Czech Republic, 9–13 May 2016* (ESA SP-740), p. 309, ESA Communications ESTEC, Noordwijk, The Netherlands.

Lainas, S., Sabatakakis, N., & Koukis, G. (2016). Rainfall thresholds for possible landslide initiation in wildfire-affected areas of western Greece. *The Bulletin of Engineering Geology*, 75, 883–896. doi:10.1007/s10064-015-0762-5

Lazecký, M., Rapanta, P., Perissinib, D., & Bakoh, M. (2014). Deformations of highway over undermined Ostrava-Svinov area monitored by InSAR using limited set of SAR images. *Procedia Technology*, 16, 414–421. doi:10.1016/j.protcy.2014.10.107.

Lee, S., & Lee, M.-J. (2006). Detecting landslide location using KOMPSAT 1 and its application to landslide-susceptibility mapping at the Gangneung area, Korea. *Advances in Space Research*, 38, 2261–2271.

Lin, J., Tao, H., Wang, Y., & Huang, Z. (2010). Practical application of unmanned aerial vehicles for mountain hazards survey. In *18th International Conference on Geoinformatics, Beijing, 2010* (pp. 1–5). doi:10.1109/GEOINFORMATICS.2010.5567777

Lowe, D. (2004). Distinctive image features from scale-invariant key points. *International Journal of Computer Vision*, 60, 91–110.

Lucier, A., De Jong, S.M., & Turner, D. (2014). Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photographs. *Progress in Physical Geography*, 38(1), 97–116.

Maas, H.G., & Kersten, T. (1997). Aerotriangulation and DEM/orthophoto generation from high-resolution still-video imagery—On the potential of digital cameras onboard an aircraft. *Photogrammetric Engineering and Remote Sensing*, 63(9), 1079–1084.

Macfarlane, D.F. (2009). Observations and predictions of the behavior of large, slow-moving landslides in schist, Clyde Dam reservoir, New Zealand. *Engineering Geology*, 109(1–2), 5–15. doi:10.1016/j.enggeo.2009.02.005

Machan, G., & Bennett, V.G. (2008). Use of inclinometers for geotechnical instrumentation on transportation projects. *Transportation Research Board of the National Academies, E-C129*, 2–37.

Mantovani, F., Soeters, R., & Van Westen, C.J. (1996). Remote sensing techniques for landslide studies and hazard zonation in Europe. *Geomorphology*, 15(3–4), 213–225.

Marcato, G., Mantovani, M., Pasuto, A., Zabuski, L., & Borgatti, L. (2012). Monitoring, numerical modelling and hazard mitigation of the Moscardo landslide (Eastern Italian Alps). *Engineering Geology*, 128, 95–107. doi:10.1016/j.enggeo.2011.09.014

Marcelino, E.V., Formaggio, A.R., & Maeda, E.E. (2009). Landslide inventory using image fusion techniques in Brazil. *International Journal of Applied Earth Observation and Geoinformation*, 11, 181–191.

Martha, T.R., Kerle, N., Jetten, V., Van Westen, C.J., & Kumar, K.V. (2010). Landslide volumetric analysis using cartosat-1-derived dems. *IEEE Geoscience And Remote Sensing Letters*, 7, 582–586.

Massey, C.A., Petley, D.N., & Mc Saveney, M.J. (2012). Monitoring, numerical modelling and hazard mitigation of the Moscardo landslide (Eastern Italian Alps). *Engineering Geology*, 128, 95–107. doi:10.1016/j.enggeo.2011.09.014

Metternicht, G., Hurni, L., & Gogu, R. (2005). Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. *Remote Sensing of Environment*, 98(2–3), 284–303. doi:10.1016/j.rse.2005.08.004

Mondini, A.C., Guzzetti, F., Reichenbach, P., Rossi, M., Cardinali, M., & Ardizzone, F. (2011). Semi-automatic recognition and mapping of rainfall induced shallow landslides using optical satellite images. *Remote Sensing of Environment*, 115(7), 1743–1757. doi:10.1016/j.rse.2011.03.006
Nicolai, J., & Wong, M.S. (2005). Satellite remote sensing for detailed landslide inventories using change detection and image fusion. *International Journal of Remote Sensing*, 26(9), 1913–1926.

Nicolai, J.E., Shaker, A., & Wong, M.S. (2006). Application of high-resolution stereo satellite images to detailed landslide hazard assessment. *Geomorphology*, 76(1–2), 68–75. doi:10.1016/j.geomorph.2005.10.001

Niethammer, U., James, M.R., Rothmund, S., Travelletti, J., & Joswig, M. (2012). UAV-based remote sensing of the super-sauze landslide: Evaluation and results. *Engineering Geology*, 128, 2–11. doi:10.1016/j.enggeo.2011.03.012

Niethammer, U., Rothmund, S., Schwanderer, U., Zeman, J., & Joswig, M. (2011). Open source image-processing tools for low-cost uav-based landslide investigations. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 38 (1C22), 161–166. doi:10.5194/isprsarchives-XXXVIII-1-C22-161-2011

Nikolakopoulos, K., Kavoura, K., Depounitis, N., Argyropoulos, N., Kougouvelas, I., & Sabatakakis, N. (2015a). Active landslide monitoring using remote sensing data, GPS measurements and cameras on board UAV. *Proceedings of SPIE*, 9644, 96440E. doi:10.1117/12.2195394

Nikolakopoulos, K., Kougouvelas, I., Argyropoulos, N., & Megaloukonomou, V. (2015b). Quarry monitoring using gps measurements and uav photogrammetry. *Proceedings Of SPIE 9644, 96440J*, 10.1117/12.2195402

Nikolakopoulos, K., Soura, K., Kougouvelas, I., & Argyropoulos, N. (2016). UAV VS classical aerial photogrammetry for archaeological studies. *Journal of Archaeological Science: Reports*, 10:685. doi:10.1016/j.jasrep.2016.09.004

Nikolakopoulos, K., Vaiopoulos, D.A., Skianis, G., Sarantinos, P., & Tsitsikas, A. (2005). Combined use of remote sensing, GIS and GPS data for landslide mapping. *IEEE IGARSS*, 7, 5196–5199.

Padwick, C., Deskevich, M., Pacifici, F., & Smallwood, S. (2010). WorldView-2 pansharpening. In *Proceedings of the ASPRS 2010 Annual Conference*, San Diego, California, p.740-753, American Society for Photogrammetry and Remote Sensing.

Powers, P.S., Chiarle, M., & Savage, W.Z. (1996). A digital photogrammetric method for measuring horizontal surficial movements on the slumgullion earthflow, Hinsdale county, Colorado. *Computers and Geosciences*, 22(6), 651–663.

Rao, X., & Tang, Y. (2014). Small baseline subsets approach of DInSAR for investigating land surface deformation along the high-speed railway. *Proceedings of SPIE*, 9260, 92601C-1-92601C-8.

Rau, J., Jhan, J., Lob, C., & Linb, Y. (2011). Landslide mapping using imagery acquired by a fixed-wing UAV. *ISPRS International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVIII-1/C22, 195–200.

Righini, G., Raspini, F., Moretti, S., & Cigna, F. (2011). Unsustainable use of groundwater resources in agricultural and urban areas: a persistent scatterer study of land subsidence at the basin scale. In Villacampa Y, Brebbia CA (Eds.), *Ecosystems and sustainable development VIII*, WIT transactions on ecology and the environment, vol. 144 (544 p.). WIT Press, Southampton, pp 81–92. doi:10.2495/ECO110071

Rosi, A., Agostini, A., Tofani, V., & Casagli, N. (2014). A procedure to map subsidence at the regional scale using the Persistent Scatterer Interferometry (PSI) technique. *Remote Sensing*, 6(10510–10522), doi:10.3390/rs6110510

Sabatakakis, N., Koukis, G., & Mourtas, D. (2005). Composite landslides induced by heavy rainfalls in urban areas: City of Patras and surrounding area, western Greece. *Landslides*, 2, 202–211. doi:10.1007/s10346-005-0002-3

Sassa, K. (2004). Preface. *Landslides*, 1, 169–171.

Skalratos, D., Procopiou, E., Stavrou, G., & Gregoriou, M. (2013). Accuracy assessment of minimum control points for UAV photography and georeferencing. *Proceedings of SPIE*, 8795, 879514. doi:10.1117/12.2028988

Snavely, N., Seitz, S.M., & Szeliski, R. (2008). The world from internet photo collections. *International Journal of Computer Vision*, 80, 189–210.

Spreafico, M.C., Perotti, L., Cervi, F., Bacenetti, M., Bitelli, G., Alena, V., … Borgatti, L. (2015). Terrestrial remote sensing techniques to complement conventional geomechanical surveys for the assessment of landslide hazard: The San Leo case study (Italy). *European Journal of Remote Sensing*, 48, 639–660. doi:10.5721/EuRJRS20154835

Stark, T., & Choi, H. (2008). Slope inclinometers for landslides. *Landslides*, 5(339–350). doi:10.1007/s10346-008-0126-3

Strozzi, T., Wegmüller, U., Tosli, B., Bitelli, G., & Spreckels, V. (2001). Land subsidence monitoring with differential SAR interferometry. *Photogrammetric Engineering & Remote Sensing*, 67(11), 1261–1270.

Stumpf, A., Malet, J.P., Kerle, N., Niethammer, U., & Rothmund, S. (2013). Image-based mapping of surface fissures for the investigation of landslide dynamics. *Geomorphology*, 186(15), 12–27. ISSN 0169-555X. doi:10.1016/j.geomorph.2012.12.010

Tofani, V., Raspini, F., Catani, F., & Casagli, N. (2013). Persistent Scatterer Interferometry (PSI) technique for landslide characterization and monitoring. *Remote Sensing*, 5, 1045–1065.

Travelletti, J., Delacourt, C., Allemand, P., Malet, J.-P., Schmittbuhl, J., Toussaint, R., & Bastard, M. (2012). Correlation of multi-temporal ground-based optical images for landslide monitoring: Application, potential and limitations. *ISPRS Journal of Photogrammetry and Remote Sensing*, 70, 39–55. doi:10.1016/j.isprsjprs.2012.03.007

Triggs, B., MaLauchlan, P., Hartley, R., & Fitzgibbon, A.W. (2000). Bundle adjustment: A modern synthesis. In B. Triggs, A. Zisserman, & R. Szeliski (Eds.), *Vision algorithms: Theory and practice* (pp. 298–372). Berlin: Springer.

Tsai, F., Hwang, J.-H., Chen, L.C., & Lin, T.H. (2010). Post-disaster assessment of landslides in southern Taiwan after 2009 Typhoon Morakot using remote sensing and spatial analysis. *Natural Hazards Earth System Sciences*, 10, 2179–2190. doi:10.5194/nhess-10-2179-2010

Turner, D., Luceier, A., & De Jong, S.M. (2015). Time series analysis of landslide dynamics using an unmanned aerial vehicle (UAV). *Remote Sensing*, 7, 1736–1757.

Vaiopoulos, A., & Nikolakopoulos, G.K. (2015). Quality evaluation of different fusion techniques applied on WorldView-2 data. *Proceedings of SPIE*, 9644, 96440W. doi:10.1117/12.2194453

Weber, D., & Herrmann, A. (2000). Contribution of digital photogrammetry in spatio-temporal knowledge of unstable slopes: The example of the Super-Saute
landslide (Alpes-de-Haute-Provence, France). *Bulletin de la Societe Geologique de France*, 171(6), 637–648.

Weirich, F., & Blesius, L. (2007). Comparison of satellite and air photo based landslide susceptibility maps. *Geomorphology*, 87(4), 352–364.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., & Reynolds, J.M. (2012). Structure-from motion photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179, 300–314.

Wieczorek, G.F., & Snyder, J.B. (2009). Monitoring slope movements. In R. Young & L. Norby (Eds.), *Geological Society of America* (pp. 245–271). Boulder, CO: Geological Monitoring. doi:10.1130/2009

Zygouri, V., Koukouvelas, I.K., Kokkalas, S., Xypolias, P., & Papadopoulos, G.A. (2015). The Nisi Fault as a key structure for understanding the active deformation of the NW Peloponnese, Greece. *Geomorphology*, 237, 142–156.