Monitoring cultural heritage sites affected by geohazards

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ABSTRACT

Currently, assessing geo-hazards in cultural heritage sites takes place after the geo-hazard has occurred. The long-term vulnerability of cultural heritage is commonly focused on the site itself, in response to environmental risks, without fully considering or understanding the entire geological and geotechnical context. However, the high costs of maintenance of cultural heritage sites directly enforce the prioritisation of the monitoring and conservation policies to ensure sustainable conservation. Monitoring the deformation of structures as well as their surroundings facilitates the early recognition of potential risks and enables effective conservation planning. This paper will present the results of the case study of the UNESCO World Heritage Site of Choirokoitia, Cyprus, where long-term low-impact monitoring systems such as UAVs and geodetic techniques were used to monitor and assess the risk from natural hazards on the archaeological site to evaluate potential geo-hazards.

Keywords: Cultural heritage, natural hazards, remote sensing, UAV, geodetic techniques

1. INTRODUCTION

Tangible cultural heritage includes various categories of monuments and sites, from cultural landscapes and sacred sites to archaeological complexes, individual architectural or artistic monuments and historic urban centres. Such places are continuously impacted and weathered continuously impacted by several environmental and anthropogenic factors, including climate change, precipitation, natural hazards, wars, etc [1-4]. However, there is limited data available regarding the effects of geo-hazards on cultural heritage sites [5]. Cultural heritage is vulnerable to geological disasters induced by earthquakes, volcanoes, floods and catastrophic landslides as well as other non-catastrophic slow-onset geohazards that can slowly affect the integrity and accessibility of the heritage, such as slow-moving landslides, sinkholes, ground settlement and active tectonics. Even if these phenomena can be responsible for large damages, they are largely neglected in the literature [6-8]. The long-term vulnerability of cultural heritage is commonly focused on the heritage itself (i.e., degradation and corrosion of building materials) in response to environmental risks [9-10], without fully considering or understanding the entire geological and geotechnical context. Currently, assessing geo-hazards in cultural heritage sites takes place after the geo-hazard has occurred. However, the high costs of maintenance of cultural heritage sites directly enforce the prioritisation of the monitoring and conservation policies to ensure sustainable conservation. Monitoring the deformation of structures as well as their surroundings facilitates the early recognition of potential risks and enables effective conservation planning [11].

On-site observation has been the most common way of monitoring cultural heritage sites and monuments in Europe. However, this procedure, that includes field surveying, ground-based data collection and periodical observations, can be time consuming and expensive, especially over large or remote areas is extremely difficult, expensive and time consuming [4]. Traditionally, deformation monitoring in cultural heritage sites is carried out by installing electrical sensors in selected structures with automatic systems for data acquisition and recording or by using portable instruments with manual reading of data taken at fixed time intervals [12-14]. However, such methods can only acquire data of the monitored structure within the cultural heritage sites, not the entire area of the site and its surrounding landscape [12]. Moreover, the installation of monitoring devices, such as optical targets, permanent GNSS stations or inclinometers, on the heritage sites and monuments can lead to aesthetic and functional impacts that can affect the integrity and availability of the heritage.

The case study of the UNESCO World Heritage Site of Choirokoitia in Cyprus is one of four case studies of the PROTHEGO project (www.prothego.eu). The focus of the PROTHEGO project is the development and validation of an

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innovative multi-scale methodology for detecting and monitoring European cultural heritage exposed to natural hazards, namely monuments and sites potentially unstable due to landslides, sinkholes, ground settlement, active tectonics as well as monument deformation, all of which could be affected by climate change and human interaction. PROTHEGO provides a new, low-cost methodological approach for the safe management of cultural heritage monuments and sites located in Europe, by integrating novel space technology based on radar interferometry (InSAR), long-term low-impact monitoring systems and indirect analysis of environmental contexts to retrieve information on ground stability and motion in the 400+ UNESCO's World Heritage List monuments and sites of Europe [3,4]. The development of the methodology for identifying cultural heritage sites affected by geo-hazards provided capacity building to the ATHENA Remote Sensing Science Center for Cultural Heritage at the Cyprus University of Technology (athena2020.eu/).

2. STUDY AREA

The field monitoring was conducted at the UNESCO World Heritage Site of Choirokoitia in Cyprus, which is one of the four demonstration sites of the PROTHEGO project. The Neolithic settlement of Choirokoitia, occupied from the 7th to the 4th millennium B.C., is one of the most important prehistoric sites in the eastern Mediterranean [15]. Included in the UNESCO World Cultural Heritage list since 1988, Choirokoitia is one of the best preserved settlements of this period in Cyprus and the Eastern Mediterranean. Located in the District of Larnaka, about 6 km from the southern coast of Cyprus, the Neolithic settlement of Choirokoitia lies on the slopes of a hill partly enclosed in a loop of the Maroni River. Occupied from the 7th to the 5th millennium B.C., the village covers an area of approximately 3 ha at its maximum extent and is one of the most important prehistoric sites in the eastern Mediterranean. It represents the Aceramic Neolithic of Cyprus at its peak, that is the success of the first human occupation of the island by farmers coming from the Near East mainland around the beginning of 9th millennium.

Figure 1. Left - Aerial view of Choirokoitia site, Center - Current condition of the site. Right - reconstruction of the houses

Excavations have shown that the settlement consisted of circular houses built from mud brick and stone with flat roofs and that it was protected by successive walls (figure 1). A complex architectural system providing access to the village has been uncovered on the top of the hill. The achievement of such an impressive construction, built according to a preconceived plan, expresses an important collective effort, with few known parallels in the Near East, and suggests a structured social organisation able to construct and maintain works of a large scale for the common good. A house consisted of several circular buildings equipped with hearths and basins arranged around a small courtyard where domestic activities took place. The houses belonged to the living, as well as to the dead who were buried in pits beneath the rammed earthen floors. Among the finds such as flint tools, bone tools, stone vessels, vegetal and animal remains, noteworthy are the anthropomorphic figurines in stone (one in clay), which point, together with funerary rituals, to the existence of elaborate beliefs. Since only part of the site has been excavated, it forms an exceptional archaeological reserve for future study. To date, 20 houses have been excavated which were constructed with limestone, clay and brick. The site depicts how people lived in the Neolithic era which was mostly through agriculture and raising domestic animals. According to UNESCO the site was officially abandoned in the 4th millenium BC. The reason for this still remains unknown [15].

3. LOCALE SCALE MONITORING

According to Margottini et al [16], the combined adoption of different survey techniques, such as 3D laser scanning and ground-based radar interferometry may be the best solution in the interdisciplinary field of cultural heritage preservation policies. Satellite radar interferometry is capable of monitoring surface deformation with high accuracy using precise ground measurements. Once vulnerable sites are identified by InSAR satellite imagery, local-scale monitoring and advanced modeling can be used to monitor the cultural heritage sites over time. The locale scale monitoring methodology includes in-situ observation and remote sensing techniques, such as PS techniques, that are used to validate the impact of natural hazards. Topographic surveying using differential GNSS, Unmanned Aerial Vehical (UAV) images, photogrammetry and InSAR data are used to map slow ground movements, which are then compared and validated with ground based geotechnical monitoring in order to evaluate cultural heritage sites deformation trend and to understand its behaviour over time. As a result, areas exposed to potential risks and their evolution in time can be identified and crucial information can be provided to decision makers in order to protect cultural and heritage sites from natural hazards.

Locale scale monitoring provides the opportunity to detect and analyze deformation phenomena for monitoring and predicting geo-hazards using field survey techniques to measure and document the extent of damage of the natural hazard on the cultural heritage site. The geodetic techniques can be used in combination with UAVs for documentation purposes and 3D modeling comparison. The aerial imagery obtained from the UAVs can be imported into Structure in Motion software to create rapid and automated generation of a point cloud model and 3D mesh model in order to document and monitor the extent of geo-hazards at the cultural heritage site. The ground based geotechnical monitoring can then be compared and validated with InSAR data to evaluate cultural heritage sites deformation trends.

3.1 Methodology

During the PROTHEGO project (HERITAGE PLUS/0314/36- Joint Programming Initiative on Cultural Heritage and Global Change (JPICH) – HERITAGE PLUS), a methodology was developed to assess the risk from natural hazards on the archaeological sites and monuments from a geospatial perspective. This paper will evaluate the field monitoring techniques used to assess the geo-hazards in the study area of Choirokoitia, Cyprus. Local scale monitoring can be used to assess the severity of these geo-hazards by using integrated field monitoring techniques. Research indicates that the integration of InSAR data and conventional surveying offers the best solution for monitoring geo-hazards in cultural heritage sites [16-18]. Geotechnical techniques are used to measure deformation over a relatively short measurement base. In-situ measurements using UAV, total station, laser scanning and GPS are then used to further measure such movements. In order to document the cultural heritage site affected by geo-hazards, UAV images and laser scanning are used [19-20].

The research methodology focused on long-term low-impact monitoring systems as well as indirect analysis of environmental contexts to investigate changes and decay of structure, material and landscape [4, 21]. The methodology for the locale scale monitoring begins with using InSAR images to identify natural hazards in the UNESCO World Heritage demonstration sites. When the InSAR ground motion data indicate that a natural hazard took place at or near the demonstration site, field monitoring and verification is necessary to document and measure the extent of the change caused by the natural hazard, if any. Documentation of the damage can be performed either close range, using laser scanning or photogrammetry, or by low altitude sensors, using UAVs and drones. Measurements for calibration of these products are taken using GNSS and total station. After the change is identified using field verification, InSAR images are again used to verify and assess the extent of the damage to the cultural heritage site [22]. The methodology is presented in figure 2.

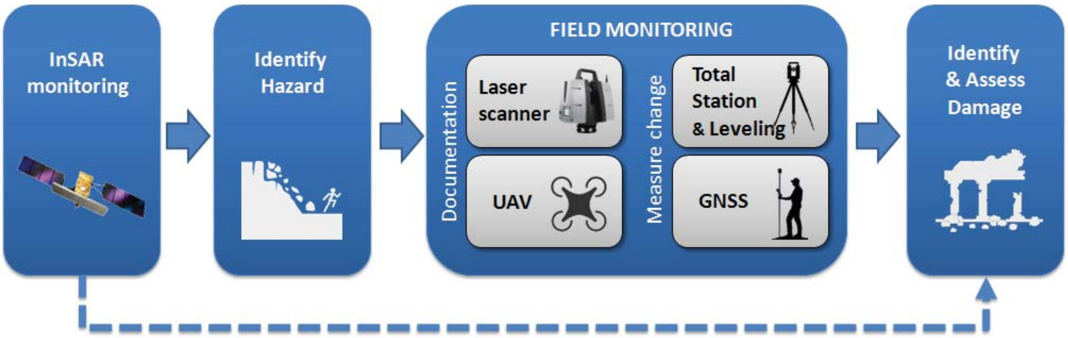


Figure 2. Methodology for local scale monitoring

3.2 Unmanned Aerial Vehicles (UAVs)

UAVs have become a common tool in cultural heritage and archaeological research as they provide higher resolution images compared with satellite imagery. Research indicates that unmanned aerial vehicles (UAVs) can be used for low-altitude imaging and remote sensing of geospatial information [23-26]. UAVs are being used for surveying cultural heritage sites due to their affordability, reliability and ease-of-use [23, 27-31]. UAV data provides more detailed surveys of the archaeological site [32-37], especially in areas that are inaccessible and/or dangerous which cannot be accessed directly using other systems or piloted aerial systems [38, 39]. Remote sensing technologies on a UAV platform are extremely useful for the detection and monitoring of cultural heritage features [24-26, 40]. UAVs can be a efficient, non-evasive and low cost resource to document cultural heritage sites 24-26, 40] and can be fitted with sensors which are able to produce an unprecedented volume of high-resolution, geo-tagged image-sets of cultural heritage sites from above [24, 25, 41-43]. UAVs provide an affordable, reliable and straightforward method of capturing cultural heritage sites, thereby providing a more efficient and sustainable approach to documentation of cultural heritage sites. Recent developments in photogrammetry technology provide a simple and cost-effective method of generating relatively accurate 3D models from 2D images [24, 27-29, 44]. To document cultural heritage site under threat from geo-hazards, UAV images can be used to create ortho-photos, dense clouds, 3D model and Digital Elevation Models [45]. The UAVs should be equipped with a 20mp camera to acquire images over the site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-image and point cloud 3D model of the demonstration site and also for comparison over temporal intervals.

Figure 3: UAVs fitted with sensors

3.3 Laser Scanners

Laser scanners have become increasingly efficient in terms of point acquisition speed, portability, user friendly and cost [46]. Laser scan technology allows user to produces a high-precision digital reference data that records condition, provides a virtual model for replication, and makes possible easy mass distribution of digital data [32, 47] of the cultural heritage site. Site documentation can be conducted using a laser scanner to monitor the site so that comparison over temporal intervals will be performed. The laser scanner cloud point can be used for further 3D modelling of the area and to generate a Digital Surface Model (DSM) of the site.

3.4 Surveying techniques

For the local-scale monitoring, surveying techniques are used to determine the absolute positions and positional changes of any point on the surface and geotechnical techniques to measure deformation over a relatively short measurement base. Surveying techniques, such as total station, leveling, and Global Navigation Satellite Systems (GNSS), are used to measure the positional changes of any point on the surface at millimeter level accuracy. They have also been successfully used for measuring deformations in archaeological areas affected by hazards [46, 48, 49]. GNSS provides location coordinates in global geographical system, highly useful in combination with other techniques, being appropriate in documenting mass targets and structural deformation [50]. Electronic data collection with total station instruments permits the quick acquisition of large amounts of field data, together with the efficient and error-free transfer of the data to a computer [51].

3.5 Geodetic techniques

A local geodetic network is first established within the cultural heritage site (figure 4). The network consists of a reference point and additional nodes, established at specific points of interest (i.e. points on peaks or ridges that may indicate/warn of a potential hazard) [20, 22]. Network points are measured regularly using satellite (GNSS) and ground measurements (via high precision total stations and levels) to estimate the potential relative motion with respect to the network reference point, during the life-span of the monitoring activity. The number of points is a function of site vulnerability parameters as indicated by geology specialists. The network nodes (or control points) need to be incorporated into the site and placed in such way as to ensure mutual visibility with the total station setup at the reference point [20, 22].

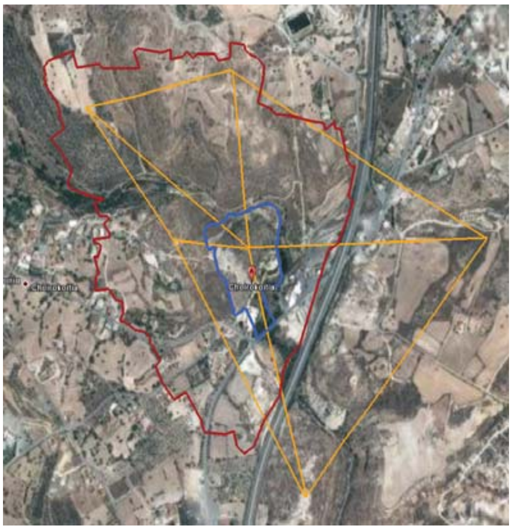


Figure 4. Geodetic Network

There are various GNSS units that can be used to establish the geodetic network. The Trimble Zephyr 2 GNSS and Leica GS15 Smart GNSS Receivers are recommended for establishing a GNSS control network (figure 5). Horizontal displacements can be measured using an industrial-grade total station, such as the Topcon MS05AXII, which has a 0.5” angular accuracy and 0.5mm range accuracy, combined with specifically designed prisms and reflective targets to achieve maximum accuracy in validating potential displacements. Vertical motion can be measured using a high-precision digital level, such as the Leica DNA03. The leveling campaign was carried out using Invar Barcode Staffs, achieving a vertical accuracy at the order of 0.3mm/km [20, 22].

Figure 5: Trimble Zephyr 2 GNSS (left) and Leica GS15 Smart GNSS Receivers (right) for establishing a GNSS control network

3.6 Ground Sensors

Monitoring of kinematic, hydrological, and climatic parameters plays a significant role in creating 3D models and simulations. Geotechnical and environmental factors enable the correlation of geo-hazard events with their triggering mechanisms and assist in identifying the causal parameters for geo-hazard monitoring and simulation [52-54]. However, geotechnical instruments for subsurface movement [23]. Most sensors for measuring earth pressure, pore water pressure, ground temperature, and vibration are point (discrete) sensors. GB-InSAR is a ground-based system that works with the same principles as space-borne sensors for monitoring ground deformation phenomena. GB-InSAR devices allow the assessment of ground deformations of faster landslides, thanks to the possibility of realizing higher frequency measurements [55, 56]. A GB-InSAR can also can be placed in front of steep slopes, which are in most cases not visible from space-borne platforms. Fiber Bragg grating (FBG) sensors can be used to measure variations of temperatures, displacements, loads, earth pressures, pore water pressures and soil moistures with high accuracy [57]. FBG sensors are still in their infancy and therefore are more suitable to be incorporated into geotechnical instrumentation to ensure accurate and real-time measurement. Capacitive sensors, which measure soil moisture levels by capacitive sensing instead of resistive sensing like other types of moisture sensor, are often used as they are made of a corrosion resistant material, giving them a long service life. Piezometers are designed to measure pore-water pressure. Piezometers in durable casings can be buried or pushed into the ground to measure the groundwater pressure at the point of installation. Water levels in the piezometer can either be logged manually (low temporal resolution) or automatically (high temporal resolution) and can be used to calculate pore-water pressures within the screened interval of the piezometer tip. Accelerometers are used to measure acceleration force, such as tilt. Typical accelerometers are made up of multiple axes, two to determine most two-dimensional movement with the option of a third for 3D positioning. Any acceleration caused due to movement in any of the axes is detected by the accelerometer. Crack meters measure the displacement between two points on the surface that are exhibiting signs of separation. A variety of other crack meters including Carlson and vibrating-wire sensors, dial gages, and mechanics feeler gages may be used to measure movement of cracks. Inclinometers are used to monitor subsurface movements and deformations for long-term, precise monitoring horizontal displacements along various points on a borehole and also to monitor the rate of movement. Tiltmeter stations proved efficient in monitoring slope stability in highly active geological environment and continue to act as substantial part of mine monitoring system. Tiltmeters are commonly attached to a surface (internal or external) of a structure and measure vertical rotation of the surface. Extensometers consist of one or more rods anchored at different depths in a borehole and a reference head at the surface. They are commonly installed vertically to measure vertical movement of the reference head relative to the anchor zone(s). They are accurate and can be used for quick and accurate measurement of relative distances between pairs of reference points on the surfaces of structures.

4. DOCUMENTATION

In order to support field monitoring, geometric documentation of the area is performed using a laser scanner, UAV systems and photogrammetry. This data will be supported and geo-referenced using a geodetic network based on total station and level measurements. The focus of the documentation is the reconstruction of the cross-sections over the identified areas of the demonstration site in order to investigate possible changes in the vertical and horizontal profiles of the remains.

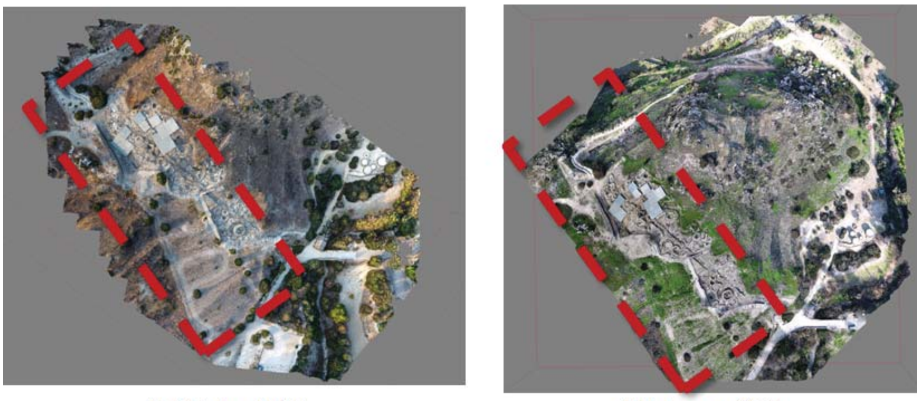
Figure 6: UAV during PROTHEGO campaign

UAVs provide an affordable, reliable and straightforward method of capturing cultural heritage sites, thereby providing a more efficient and sustainable approach to documentation of cultural heritage sites. Under the framework of the PROTHEGO project, hundreds of images of the Choirokoitia site were taken using a UAV with an attached high resolution camera. As part of the locale-scale monitoring of the Choirokoitia demonstration site in the PROTHEGO project, a UAV with an attached 20MP camera was used to acquire images over the site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-image of the demonstration site and also for comparison over temporal intervals [54]. The images were processed using photogrammetry, where the digital images acquired from the UAV are interpolated in order to create high resolution, scaled and georeferenced 3-D models from them.

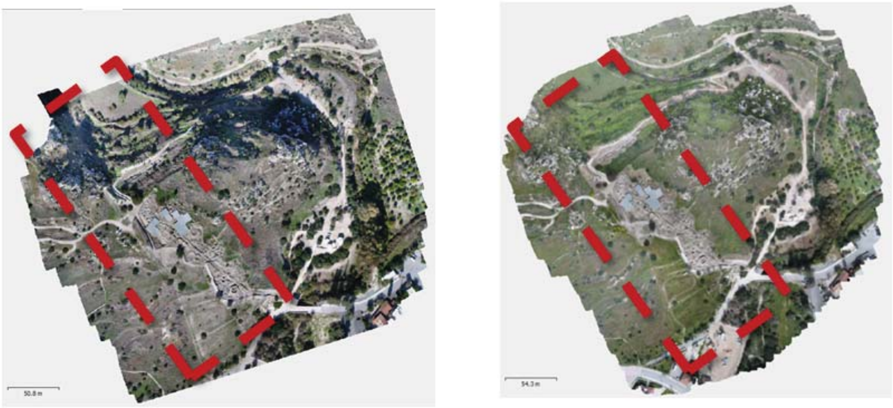
Images were taken using UAVs on 29 October, 2016, 2 February, 2017, 11 November and 8 March, 2018, with approximately 450 images taken of the Choirokoitia site during each UAV flight. Ground Control Points (GCP) were applied to correct the scale and geo-reference the model. The images were then pre-processed by removing the lens distortion and then processed using the Agisoft Photoscan Professional software. Figure 7 features the Orthophoto of Choirokoitia site 29 October, 2016, including the resolution of detail.

Figure 7. Ortho-photo of the Choirokoitia site, with resolution of 2.26 cm/pix

All clear images with sufficient overlap were included in the processing in order to generate a dense point cloud of the Choirokoitia site. The 3D point cloud generation for all four monitoring surveys is shown in Figure 8.



29 October, 2016 **2 February, 2017**



11 November, 2017 **7 March, 2018**

Figure 8. Point cloud generations of Choirokoitia site (outlined in red)

As is evident from Figure 8, there was a dramatic difference in the level of vegetation present at the site on the dates that the images were acquired. The October 2016 and November 2017 images show sparse vegetation while the images acquired in February 2017 and March 2018 show significantly more vegetation present at the site. As it was easier to identify vegetation in the images acquired in the winter campaign due to the colour and morphology of the vegetation, masking was done in order to subtract the vegetation from the model in order to generate the DEM of the ground surface. This was done by using interpolation of the areas where the vegetation was previously present using the images acquired in October, 2016 and February 2017. Following, a contour map of the area was generated using stitch imaging using the DEM model without vegetation (figure 9).

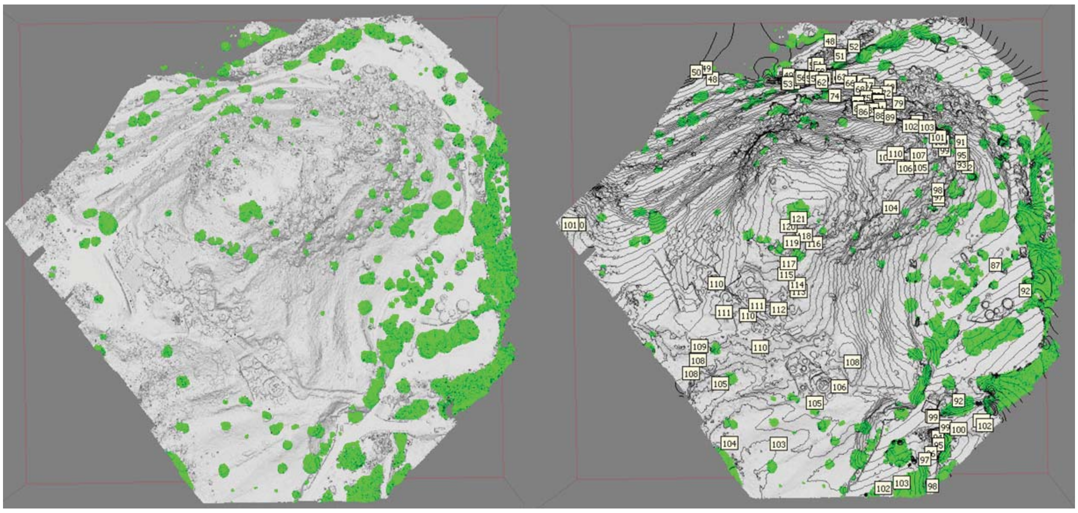
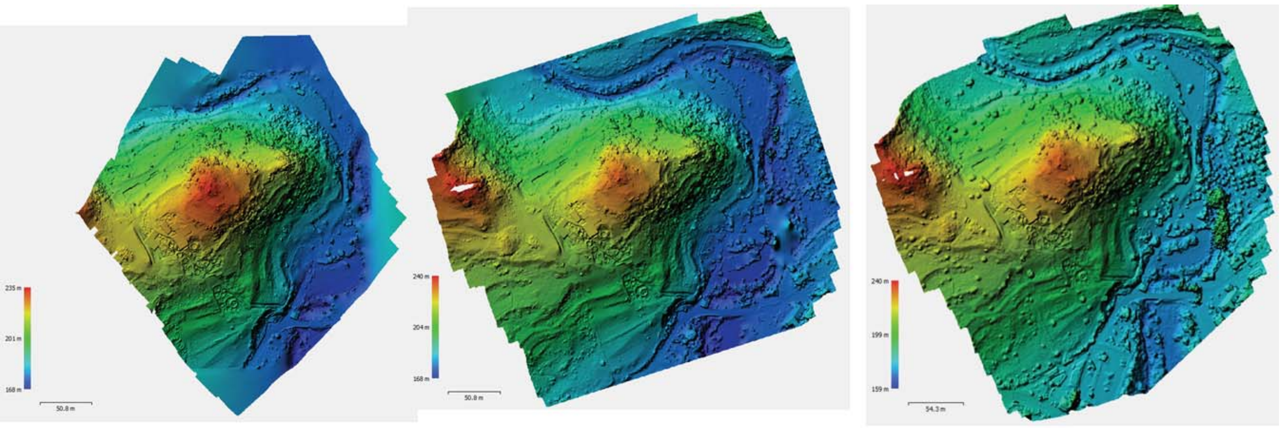


Figure 9. Vegetation Subtraction and contour generation

Digital Elevation Models (DEMs) were generated to examine any possible changes in the case study area over time. Figure 6 features the DEMS generated based on the images from February, 2017, November, 2017 and March, 2018. As is evident in Figure 10, there is a slight shift at the top peak of the hill.



2 February, 2017

11 November, 2017

7 March, 2018

Figure 10. DEM models of the Choirokoitia site

The final 3D model of the Choirokoitia site is presented in Figure 11.

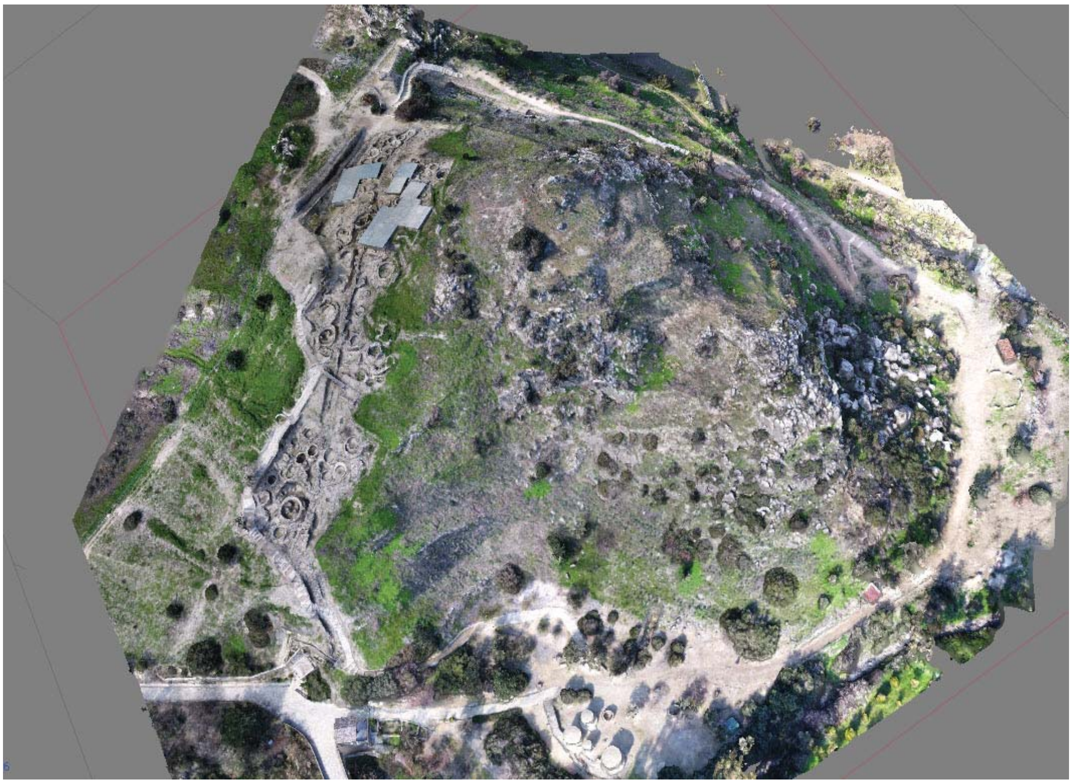


Figure 11. 3D model of the Choirokoitia site generated with UAV images

4.1 Results

Table 1 features the results of the GNSS control network during the study time frame. There were 4 GPs sites which measured displacement east (DE), Displacement North (DN) and Displacement Up (DU). The coordinates used are based on the Cyprus Local Transverse Mercator projection system (LTM) which is based on the Datum Cyprus Geodetic Reference System of 1993 (CGRS93) that uses the ellipsoid WGS84.

Table 1. Results of GNSS Control network

Site	Coordinates	DE	DN	DU
GPS1	231524.820 / 352001.675	+0.0023	-0.0025	-0.0027
GPS2	231314.725 / 351974.690	+0.0022	-0.0001	+0.0017
GPS3	231344.434 / 351922.148	+0.0000	+0.0000	+0.0000
GPS4	231453.791 / 351980.692	+0.0024	+0.0001	**-0.0203**

The results of the GNSS control network found a change of 2mm during the 24 months of the monitoring period of the site, which is indicated in bold in Table 1. As well, a PSI analysis was conducted of the Choirokoitia general area to determine any micro-movements in the area. For the PSI analysis 26 Cosmos Skymed SAR images from the years 2011-2017. For the dates defined, the points exhibit an average of 0.33 mm rate of movement per year (velocity). The results of the PSI analysis found displacement at the same area as the GNSS control network. Longer-term monitoring of the site is required in order to diagnose the severity of the displacement.

5. CONCLUSIONS

The case study of Choirokoitia, Cyprus provides an example of how to detect and analyze deformation phenomena for monitoring and predicting geo-hazards using InSAR ground motion data and field survey techniques to measure and document the extent of damage of the natural hazard on the cultural heritage site. The InSAR data, GNSS, total station and level were used to measure the micro-movements, while the UAV and photogrammetry are used for documentation purposes and 3D modeling comparison. PSI analysis and GNSS Control Network of the cultural heritage site provide the ability to identify displacement as a result of ground movements, which indicates the need for longer-term monitoring of the site to diagnose the severity of the geo-hazards. Local-scale monitoring data is the base for the development of geological and geotechnical modelling of the investigated sites, which will provide evolution models for the deformation processes affecting the heritage sites in order to recognize the best mitigation strategies and to evaluate the effectiveness of these actions for cultural heritage protection.

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