Monitoring Cultural Heritage Sites Affected by Geo-Hazards Using In Situ and SAR Data: The Choirokoitia Case Study

Kyriacos Themistocleous and Chris Danezis

Abstract This chapter focuses on the different methods for monitoring cultural heritage and archaeological sites affected by geo-hazards through the integrated method of using satellite imagery and field measurements. The Choirokoitia case study, which was one of the four UNESCO World Heritage list sites under the auspices of the PROTHEGO project, will be examined. 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 interferometric synthetic aperture radar (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.

Keywords Cultural heritage · Archaeology · Natural hazards · Remote sensing · UAV · Geodetic techniques · Photogrammetry

Introduction

Research indicates that archaeological and cultural heritage (ACH) sites are vulnerable to geological disasters, such as earthquakes, flooding, volcanoes, and catastrophic landslides, as well as slow-moving geo-hazards that take place over time, such as ground settlement, sinkholes, and slow-moving landslides (Themistocleous 2018; Agapiou et al. 2015, 2016; Margottini et al. 2016; Themistocleous et al. 2016a). However, the effects of geo-hazards on ACH sites have not been examined (Themistocleous et al. 2016b; Gutiérrez and Cooper 2002; Rohn et al. 2005; Canuti et al. 2009). The prevailing research tends to focus on the cultural heritage site in response to the geo-hazard and how to correct damage, instead of focusing on the

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underlying geological and geotechnical context of the hazards in order to prevent damage to ACH sites by recognizing risks in order to establish effective conservation planning (Brimblecombe 2000; Fort et al. 2006; Tang et al. 2016).

The documentation of ACH sites has traditionally been expensive and labor-intensive since it involves field surveying, ground-based data collection, and periodical observations (Themistocleous et al. 2016a), which is especially difficult over large archaeolandscapes and remote areas. The PROTHEGO (PROTection of European Cultural HEritage from GeO-hazards) 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 long-term low-impact monitoring systems, such as UAVs and geodetic techniques, interferometric synthetic aperture radar (InSAR) systems, and indirect analysis of environmental contexts to monitor and assess the risk of geo-hazards in the 400+ UNESCO's World Heritage List (WHL) of monuments and sites of Europe. The project includes the 395 monuments of UNESCO in Europe to monitor geo-hazards, with case studies conducted in 4 UNESCO sites in England, Spain, Italy, and Cyprus.

This paper will present an overview of the monitoring techniques using in situ and Earth observation for ACH sites affected by geo-hazards that are potentially unstable due to landslides, sinkholes, settlement, subsidence, active tectonics, as well as structural deformation. The Cyprus case study of Choirokoitia will be used as an example of how the PROTHEGO methodology can be utilized to identify geo-hazards.

Best Practices for Diagnosis, Monitoring, Mitigating, and Preserving Cultural Heritage Sites

The PROTHEGO project developed a methodology to identify cultural heritage sites that were at risk for geo-hazards. In order to identify the level of risk of the UNESCO WHL sites, a multi-criteria risk assessment is used to prioritize the severity of the geo-hazard, as well as to establish mitigation and conservation efforts (Silvestrou and Themistocleous 2018). To effectively assess the level of risk, the ACH sites must first be diagnosed through a condition assessment in order to identify damage and risks to estimate the physical condition of the site (Themistocleous et al. 2017a, 2018a, b). The condition assessment (which includes both qualitative and quantitative data) assesses the condition (level of damage) of the heritage place, level of risk and vulnerability, significance and value of the heritage place and prioritization of heritage and activities, and assessment of recovery needs. Best practices for the conservation of cultural heritage sites include diagnosis, monitoring, mitigation, and preservation of the site, as shown in Fig. 1.

Traditional methods of diagnosis include photographs, drawings, and topographical surveys. Currently, more innovative methods of diagnosing and documenting archaeological and cultural heritage sites include laser scanners, thermal cameras,

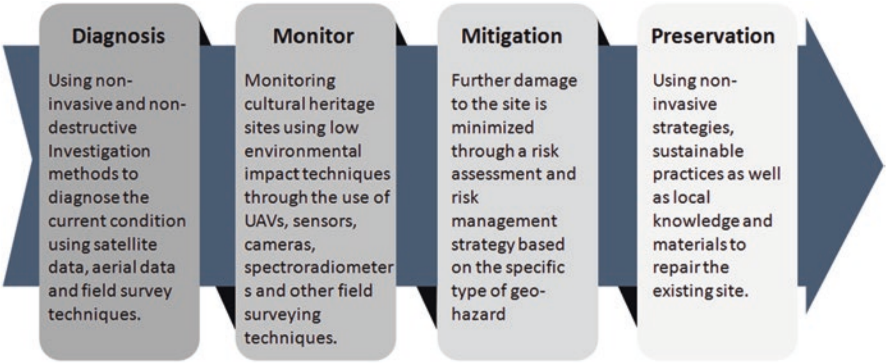


Fig. 1 Best practices for conservation of cultural heritage sites

Lidar, and digital images taken from an Unmanned Aerial Vehicle (UAV), which are used in conjunction with photogrammetry to create ortho-photos, 3D models, digital elevation models, and simulations (Themistocleous et al. 2017b, 2018a, b; Themistocleous 2017). Additional diagnostic techniques include ground-penetrating radar, laser scanning surveys, discontinuity mapping, infrared thermography, and kinematic analysis.

Monitoring focuses on the extent of the damage, deterioration, movement, humidity, precipitation, erosion, etc. of the ACH sites. Traditional methods of monitoring include in situ measurement campaigns, field measurements, and digital levels, which are time-consuming and labor-intensive. Low-impact monitoring includes techniques such as satellite radar interferometry, ground-based interferometry, total station, and traditional geotechnical network. Recent methods of monitoring are increasingly innovative and include satellite and aerial imagery, field surveying, wireless networks, GNSS control network, and 3D modeling and simulation. Sensors used to measure movement, slope, deformation, humidity, and precipitation include accelerometers, inclinometers, levelometer, crack-measuring devices, tiltmeters, piezometers, etc.

Once the ACH site has been diagnosed and monitored, further damage needs to be minimized. Mitigation strategies very much depend on the type of geo-hazard. Mitigation strategies include technical analysis of building materials, structural assessment of the site, condition assessment of the site, and simulation models. Multidisciplinary scientific approach is needed for a thorough risk assessment which should encompass multiple settings at a given site. Risk assessment procedures should be identified for determining more appropriate risk reduction strategies in the decision-making process. Mitigation requires a general description of the ACH site, the identification of the causative factors and triggering mechanism of the geo-hazard, and the use of traditional techniques to minimize risk as well as constant monitoring, stability management, and awareness. As well, an integral natural risk management for appropriate risk mitigation should be established for different priority levels of ACH sites by geo-hazards.

Preservation refers to the repair and replacement work necessary to prevent further damage to the site, preferably using the same, similar, or compatible materials. Preservation activities need to be aesthetically pleasing and complement the cultural heritage site. It is recommended that support structures and scaffolding be included, depending on the type of geo-hazard. The preservation techniques should reduce existing vulnerability to prevent the creation of new risks. Guidelines and intervention criteria should be established in order to preserve the site. Early warning, detection, and prevention actions should receive as much importance as post-disaster monitoring and remedial actions. Sustainable mitigation practices are necessary for preservation which include (a) effective solutions based on the best possible information available in order to solve the problem at hand, (b) environmental impact that is noninvasive and emphasizes the maximum preservation of the original aspect of the site, (c) sustainability by enhancing traditional knowledge and sustainable practices that have the maximum benefit of local experience, and (d) socioeconomic impact, by using local materials, workers, and artisans to maximize the reproducibility of conservation in case of future interventions.

Choirokoitia Study Area

The UNESCO World Heritage Site of Choirokoitia in Cyprus, which is one of the four case studies of the PROTHEGO project (see Fig. 2). The Neolithic settlement of Choirokoitia, occupied from the 7th to the 4th millennium BC, is one of the most important prehistoric sites in the eastern Mediterranean (UNESCO World Heritage List 2016). Choirokoitia is one of the best preserved settlements of this period in

Fig. 2 Choirokoitia site

Fig. 3 Reconstruction of the houses in Choirokoitia

Cyprus and the eastern Mediterranean. The site is located in the district of Larnaka, about 6 km from the southern coast of Cyprus, and lies on the slopes of a hill partly enclosed in a loop of the Maroni River. Occupied from the 7th to the 5th millennium BC, 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, which is the first human occupation of the island by farmers coming from the Near East mainland around the beginning of the 9th millennium. The site depicts how people lived in the Neolithic era which was mostly through agriculture and raising domestic animals.

Archaeological excavations at Choirokoitia consist of circular houses built from mudbrick and stone with flat roofs that were protected by successive walls (Fig. 3). On the top of the hill, a complex architectural system providing access to the village has been uncovered, which indicates that the settlement was built according to a preconceived plan. This indicates an important collective effort and suggests a structured social organization able to construct and maintain works of a large scale for the common good. The Choirokoitia site includes several circular buildings equipped with hearths and basins (assumed to be houses) arranged around a small courtyard where domestic activities took place.

To date, 20 houses have been excavated which were constructed with limestone, clay, and brick. According to UNESCO, the site was officially abandoned in the 4th millennium BC for unknown reasons.

Local-Scale Monitoring

Current research states that the integration of different survey techniques and ground-based radar interferometry are the most effective solution for monitoring and preserving ACH sites (Margottini et al. 2015). Satellite radar interferometry is capable of monitoring surface deformation with high accuracy using precise ground measurements. When ACH sites vulnerable to geo-hazards are identified, on-site observations and modeling can be used to monitor the area over time. The local-scale monitoring methodology includes in situ observation and remote sensing techniques that are used to identify and measure the impact of the geo-hazard affecting the ACH site. The combination of topographic surveying, aerial images from UAVs, photogrammetry, and InSAR data can be used to map slow ground movements in the area of interest. This data is then compared and validated with ground-based geotechnical monitoring in order to evaluate the deformation trend at the ACH site. Also, advanced modeling is used to predict the effect of the geo-hazard in the area if preventive measures are not taken. As a result, ACH sites exposed to potential risks can be identified, and vital information can be provided to decision-makers in order to protect cultural and heritage sites from natural hazards.

Local-scale monitoring provides the opportunity to detect and analyze deformation phenomena for assessing the severity of 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, both in the short-term and the long-term (Margottini et al. 2015, 2018; Novellino et al. 2018). Geotechnical techniques are used to measure deformation over a relatively short measurement base, while in situ measurements using UAV, total station, laser scanning, and GPS are then used to measure such movements over extended time periods. In order to document the cultural heritage site affected by geo-hazards, UAV images and laser scanning are used (Themistocleous 2017; Themistocleous et al. 2017b).

To identify and assess geo-hazards at ACH sites, a methodology was developed for local-scale monitoring in order to assess risk from a geospatial perspective, as featured in Fig. 4. The 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 (Themistocleous 2018; Themistocleous et al. 2016a). The first step of the methodology begins with using InSAR images to identify geo-hazards. Once InSAR ground motion data identify that a natural hazard has taken place at or near the ACH site, field monitoring is necessary to document and measure the severity of the change caused by the natural

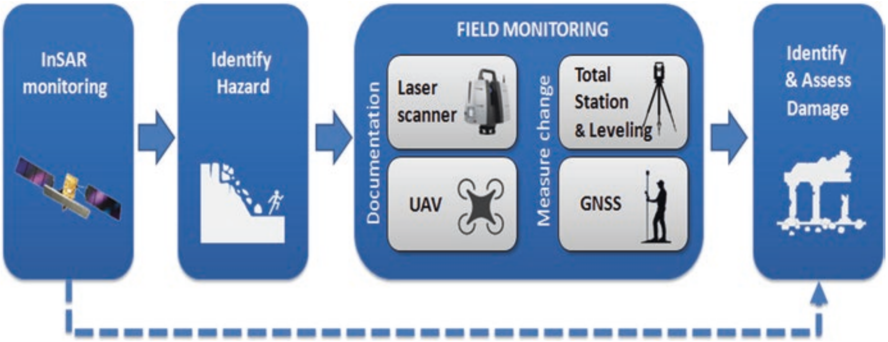


Fig. 4 Methodology for local-scale monitoring

hazard, if any. Documentation of the change can be performed either close range, using laser scanning, photogrammetry GNSS, and total stations, or by low-altitude sensors, using UAVs and drones. Once the changes are identified using field verification, InSAR images are again used to verify and assess the extent of the damage to the cultural heritage site (Themistocleous et al. 2018c).

Satellite Imagery

Synthetic Aperture Radar (SAR) imaging satellites, Interferometric SAR (InSAR), and Persistent Scatterers (PS) processing techniques (Rosen et al. 2000; Ferretti et al. 2011; Crosetto et al. 2010) are capable of measuring changes on Earth with millimeter precision. As a result, they can identify subtle and long-term changes that lead to damage to ACH sites.

Satellite Synthetic Aperture Radar (SAR) images are processed with multi-interferogram methods, such as the Persistent Scatterers (PS) technique, to identify ground displacement in the areas of interest, thereby providing an effective solution to measure large-scale surface deformations from space (Ferretti et al. 2011; Zhou et al. 2015; Hooper et al. 2012; Chen et al. 2012, 2013; Cigna et al. 2012, 2014). Differential Interferometric SAR (InSAR) methods integrate the radar returns from two or more radar scenes over the same area to detect changes occurred between acquisitions, thereby monitoring subtle ground movements across wide areas with millimeter accuracy (Chen et al. 2015; Tapete et al. 2013; Zhou 2013; Evans and Farr 2007; Polcari et al. 2015). Research indicates that SAR data can provide powerful information for archaeological and cultural heritage research, including archaeolandscapes, site detection, feature extraction (buried or emerging archaeological remains), change detection, and structural monitoring (Cigna et al. 2012, 2013; Lasaponara and Masini 2013; Tapete et al. 2012, 2016).

The Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) technique is used for monitoring and measuring ground displacements with a millimetric resolution and to overcome the effects of natural decorrelation and atmosphere. The technique is also suitable for slope stability monitoring if movement is either creeping or moderate movement (on the order of <10 cm/year). The PSInSAR technique uses a stack of SAR interferograms and determines the motion history for pixels that are identified to have temporal phase stability (i.e., pixels whose overall response is dominated by a strong back-scatterer). PS interferometry can be performed by relying on fixed targets, often called coherent scatterers or point scatterers (PS). In cases where few natural persistent scatterers exist in the area of interest, corner reflectors can be installed to provide artificial radar scatterers for use in PSI analyses. These devices installed in situ provide a strong response in the SAR images resulting in good interferometric phases to derive the deformation estimates. Corner reflectors are usually trihedral and vary in size depending upon the radar wavelength for which they are designed. In remote areas these interferometric outputs can be compared with in situ measurements (GPS, leveling, inclinometers) and used as initial input for any geotechnical modeling.

Unmanned Aerial Vehicles (UAVs)

In recent years, UAVs have become a common tool in cultural heritage and archaeological research since they provide higher resolution images compared with satellite imagery. They are used for surveying cultural heritage sites due to their affordability, reliability, and ease of use (Themistocleous et al. 2014a, b, c, 2015a, b, c; Agapiou et al. 2013; Lo Brutto et al. 2014; Burkhart et al. 2014; Colomina and Molina 2014). UAV data provides more detailed surveys of the archaeological site (Hassani 2015; Remondino and Rizzi 2009; El-Hakim et al. 2004; Gruen et al. 2005; Guidi et al. 2009; Rönnholm et al. 2007), especially in areas that are inaccessible and/or dangerous which cannot be accessed directly using other systems or piloted aerial systems (Everaerts 2008; Eisenbeiß 2009). As well, UAVs can be used for low-altitude imaging and remote sensing of geospatial information (Themistocleous et al. 2014a, b, c; Colomina and Molina 2014). Remote sensing technologies on a UAV platform (see Fig. 5) are extremely useful for the detection and monitoring of ACH sites since they 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 (Themistocleous et al. 2014a, b, c; Agapiou et al. 2013; Kostrzewa et al. 2003; Ruffino and Moccia 2005; Scholtz et al. 2011).

UAVs provide an affordable, reliable, and straightforward method of documenting ACH sites. Recent developments in photogrammetry technology provide a simple and cost-effective method of generating relatively accurate 3D models from 2D images (Themistocleous et al. 2014a, 2015a, b, c; Ioannides et al. 2013). To document ACH sites affected by the geo-hazards, aerial images taken from a UAV can be used to create ortho-photos, dense clouds, 3D model, and digital elevation models (Themistocleous 2017), as featured in Fig. 6. It is necessary for the UAV to be equipped with a high-resolution RGB camera to acquire images over the area of interest. The area should have fixed ground control points (GCPs) for georeferencing in order to produce a photogrammetric ortho-photo and point cloud 3D model of the area of interest and for comparison over temporal intervals.

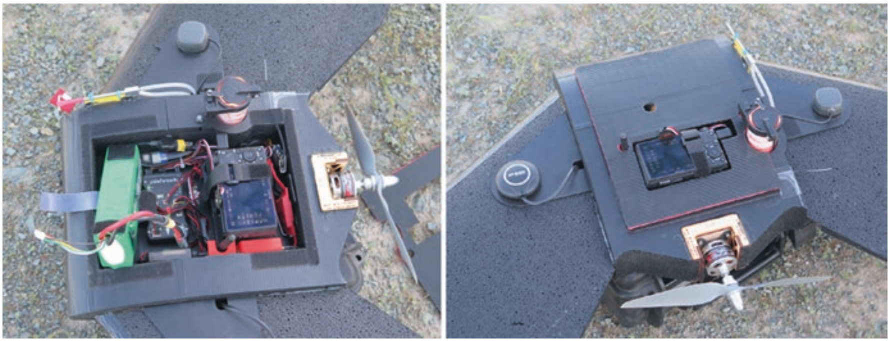


Fig. 5 UAVs fitted with sensors

Fig. 6 UAV flight over Choirokoitia UNESCO site

To process the aerial images taken from the UAV, it is necessary to position GCPs over the entire area prior to the flight to make the necessary corrections during the post-processing of the image to ensure the correct scale of the model. It is recommended that the GCPs be recorded with a double frequency GNSS system with estimated accuracy of less than 2 cm. The UAV with RGB camera will be flown over the area of interest using flight planning software to create a predetermined flight path, to ensure significant image coverage. The aerial images should have an 80% overlay within each image so that single images can be processed with photogrammetry in order to generate ortho-photos and create 3D models.

Laser Scanners

Laser scanners have become increasingly efficient in terms of point acquisition speed, portability, user-friendliness, and cost (Fassi et al. 2013). The technology allows user to produce a high-precision digital reference data that documents the condition of the ACH site so that comparisons over temporal intervals can be performed, provides a virtual model for replication, and makes possible easy mass distribution of digital data of the ACH site (Hassani 2015; Vilceanu et al. 2015). The laser scanner can be used for further 3D modeling of the area and to generate a digital surface model (DSM) of the site.

Surveying Techniques

Surveying techniques are used to determine the absolute positions and positional changes of any point on the surface, while geotechnical techniques are used to measure deformation over a relatively short measurement base. Surveying techniques, such as total station, leveling, and global navigation satellite systems (GNSS), measure the positional changes of any point on the surface at millimeter level accuracy and have successfully been used for measuring deformations in archaeological areas affected by hazards (Polcari et al. 2015; Fassi et al. 2013; Jiang et al. 2012). The GNSS provides location coordinates in global geographical system, which are highly useful in combination with other techniques for documenting mass targets and structural deformation (Hassani 2015). The total station is capable of acquiring large amounts of field data, together with the efficient and error-free transfer of the data to a computer (Haddad 2011).

Geodetic Techniques

A local geodetic network consists of a reference point and additional nodes, established at specific points of interest, such as points on peaks or ridges that may indicate/warn of a potential hazard (Themistocleous et al. 2017a; Themistocleous 2017). Network points are measured often using satellite (GNSS) and ground measurements (high-precision total stations and levels) to measure the potential relative motion with respect to the network reference point during the life-span of the monitoring activity, as shown in Fig. 7. The number of points in the network is largely a function of the geological vulnerability parameters of the area of interest. The network nodes (or control points) need to be incorporated into the site and placed in such way in order to ensure mutual visibility with the total station setup at the reference point (Themistocleous et al. 2017a; Themistocleous 2017).

Various GNSS units can be used to establish the geodetic network. In this case study, the Trimble Zephyr 2 GNSS and Leica GS15 Smart GNSS Receivers were used for establishing a GNSS control network, as shown in Fig. 8. The Trimble Zephyr 2 GNSS offers robust low-elevation tracking and submillimeter phase center repeatability, making it ideal for base station applications, as it can withstand shock and vibration. It is capable of multipath reduction and low-elevation satellite tracking. The Trimble Zephyr 2 GNSS supports submillimeter phase center accuracy and supports signals from GPS L2C/L5, GLONASS, Galileo, OmniSTAR, and SBAS. The Leica GS15 Smart GNSS Receivers are recommended as they adjust to any environment and deliver the most accurate results. They use multifrequency, consisting of GPS/GLONASS/Galileo/BeiDou. They are also static (phase) with long observations and have external data links for GSM/GPRS/UMTS/CDMA and UHF/VHF modem.

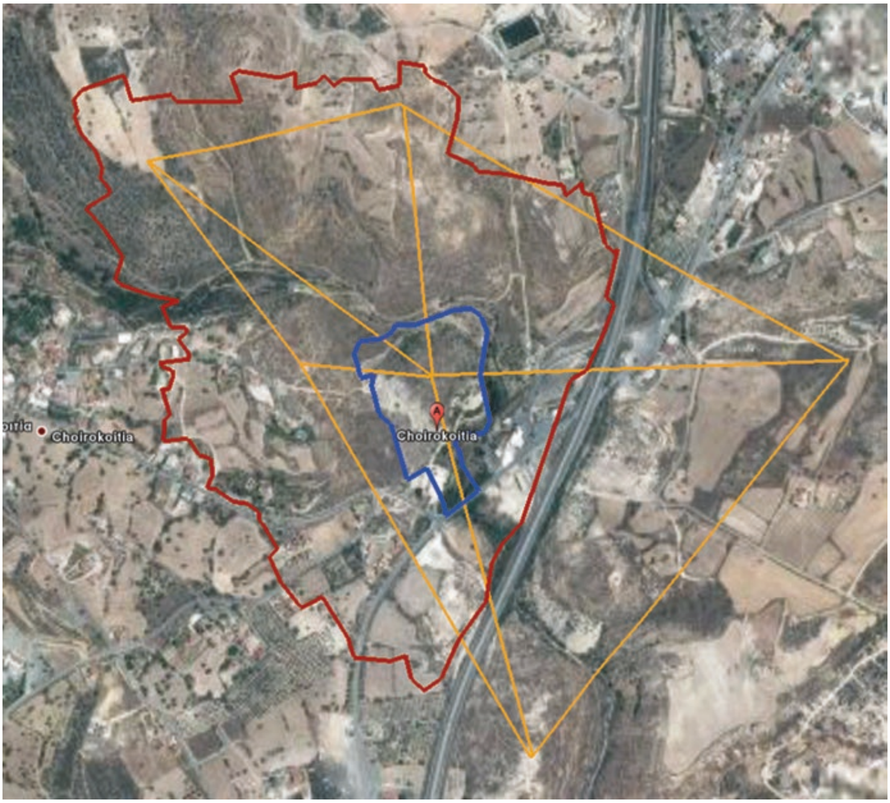


Fig. 7 Geodetic Network at Choirokoitia

Fig. 8 Trimble Zephyr 2 GNSS (left) and Leica GS15 Smart GNSS Receivers (right) for establishing a GNSS control network

Horizontal displacements can be measured using an industrial-grade total station, such as the Topcon MS05AXII, which has a 0.5″ angular accuracy and 0.5 mm 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 will be carried out using Invar Barcode Staffs, achieving a vertical accuracy at the order of 0.3 mm/km (Themistocleous et al. 2017a; Themistocleous 2017).

Ground Sensors

Geotechnical and environmental ground sensors enable the correlation of geo-hazard events with their triggering mechanisms and assist in identifying the causal parameters for geo-hazard monitoring and simulation (Themistocleous et al. 2017b, 2018a, b). However, geotechnical instruments for subsurface movement monitoring, such as inclinometers and extensometers, are incapable of large-scale and long-distance monitoring (Zhu et al. 2017). Most sensors for measuring earth pressure, pore water pressure, ground temperature, and vibration are point (discrete) sensors.

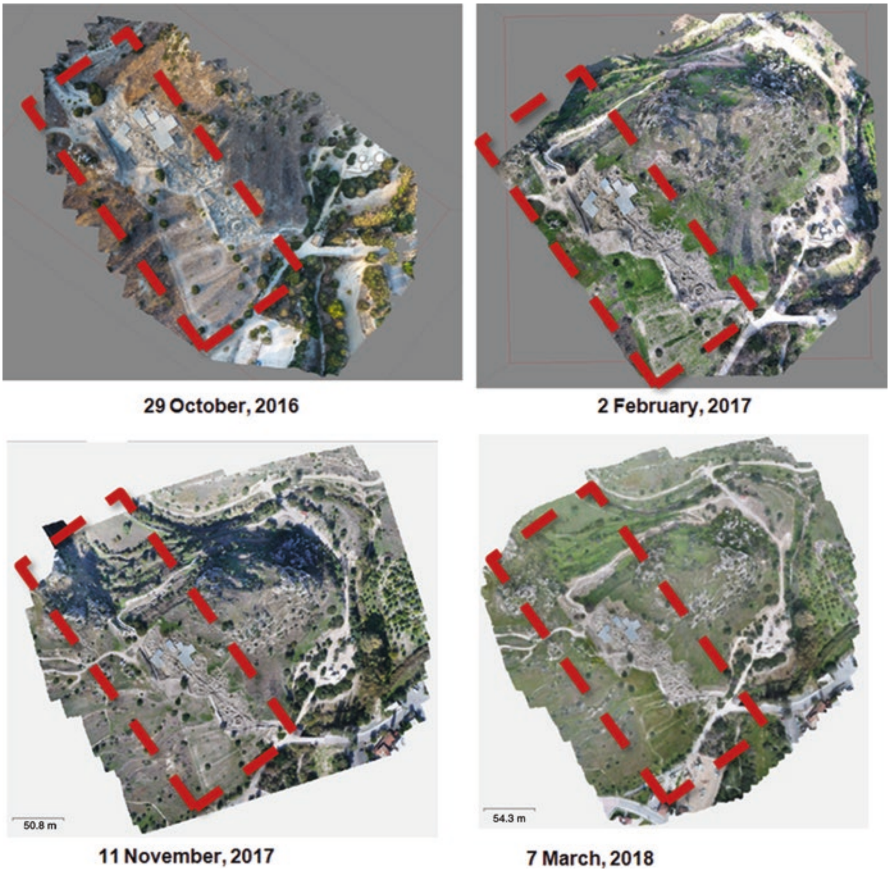
GB-InSAR provide continuous monitoring of displacements from few millimeters per day up to 1 or more meters per day over unstable areas. GB-InSAR devices allow the assessment of ground deformations of faster landslides, by recording higher-frequency measurements (Corsini et al. 2006; Noferini et al. 2008). Fiber Bragg grating (FBG) sensors measure variations of temperatures, displacements, loads, earth pressures, pore water pressures, and soil moistures with high accuracy (Zhu et al. 2017). 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 measure soil moisture levels by *capacitive sensing* instead of resistive *sensing* like other types of moisture sensor. Since they are resistant to corrosion, they are often used for long-term monitoring of a site. Piezometers measure pore water pressure. They can be buried or pushed into the ground to measure the groundwater pressure at the point of installation. Accelerometers measure acceleration force, such as tilt. They tend to be made up of multiple axes so that 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 monitor subsurface movements and deformations for long-term, precise monitoring horizontal displacements along various points on a borehole and also monitor the rate of movement. Tiltmeter stations monitor slope stability in highly active geological environment. They are commonly attached to a surface (internal or external) of a structure and measure vertical rotation of the surface. Extensometers measure vertical movement. Due to their accuracy, they can be used for quick and accurate measurement of relative distances between pairs of reference points on the surfaces of structures.

Case Study Results

To support field monitoring, geometric documentation of the area was performed using a laser scanner, UAV systems, and photogrammetry. The data was geo-referenced using a geodetic network based on total station and level measurements. The focus of the documentation was 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 study area. Under the framework of the PROTHEGO project, aerial images of the Choirokoitia site were taken using a UAV with an attached high-resolution 20MP RGB camera to acquire images over the site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-photo of the site and for comparison over temporal intervals (see Fig. 9). The aerial images were processed using photogrammetry, where the digital images acquired from the UAV were interpolated in order to create high-resolution, scaled, and geo-referenced 3D models from them.

Aerial images of the Choirokoitia site using UAVs were taken on 29 October 2016, 2 February 2017, and 11 November and 8 March 2018, with approximately 450 images taken of the Choirokoitia site during each UAV flight. GCPs were used to correct the scale and geo-reference the model. The images were then preprocessed by removing the lens distortion and then processed using the Agisoft PhotoScan Professional software.

Fig. 9 Ortho-photo of the Choirokoitia site, with resolution of 2.26 cm/pix


29 October, 2016

2 February, 2017

11 November, 2017

7 March, 2018

Fig. 10 Point cloud generations of Choirokoitia site (outlined in red)

All clear images with an overlap of 80% 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 Fig. 10.

There was a notable difference in the level of vegetation present at the Choirokoitia 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. Since it was easier to identify vegetation in the images acquired in the winter campaign due to the color and morphology of the vegetation, masking was done in order to subtract the vegetation from the model to generate the DEM of the ground surface. This was done by using interpolation of the areas with vegetation, 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 (Fig. 11).

Digital elevation models (DEMs) were generated to examine any possible changes in the case study area over time. The DEMs generated based on the images

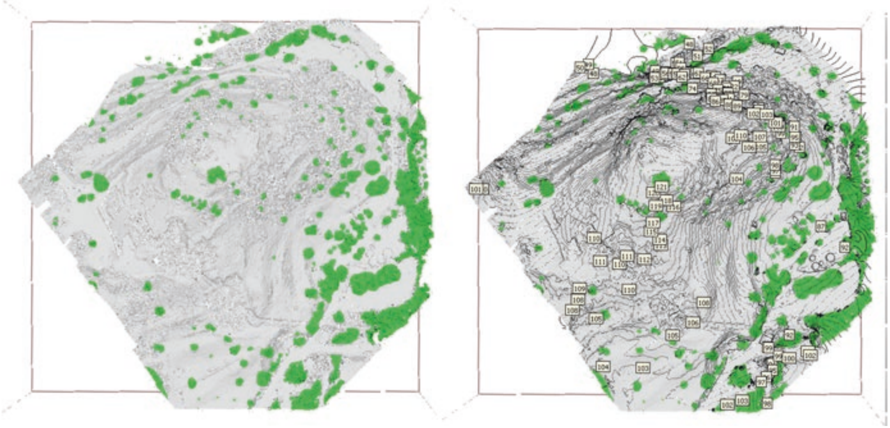


Fig. 11 Vegetation Subtraction and contour generation

from February 2017, November 2017 and March 2018 are shown in Fig. 12. As is evident, there is a slight shift at the top peak of the hill.

The final 3D model of the Choirokoitia site is presented in Fig. 13.

Table 1 features the results of the GNSS control network during the study time frame. There were four 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 (LTM) projection system which is based on the Datum Cyprus Geodetic Reference System of 1993 (CGRS93) that uses the ellipsoid WGS84. The results of the GNSS control network found a change of 2 cm during the 24 months of the monitoring period of the site.

Rockfall Modeling

A rockfall simulation model was created through the collaboration of the Cyprus University of Technology with the University of Milano-Bicocca (Valagussa et al. 2018). The rockfall runout simulation was performed by using the 3D model HY-Stone (Agliardi and Crosta 2003; Crosta et al. 2004). Such 3D models have the ability to simulate block motion along a slope by including lateral dispersion of trajectories resulting from large- and small-scale morphological complexity (Agliardi and Crosta 2003; Crosta et al. 2004; Descoeudres and Zimmermann 1987; Guzzetti et al. 2002; Dorren et al. 2006). The results were spatially distributed over the entire study area, without any interpolation of data computing along specific trajectories or imposing predetermined fall direction. The topography is by a raster DEM, which was converted in a vector topographic model (Triangulate Regular Network) (Guzzetti et al. 2002) for the modeling of impact and rolling. The stochastic nature of rockfall processes was introduced as a function of model spatial resolution and by random sampling most parameters from different PDF, such as uniform,

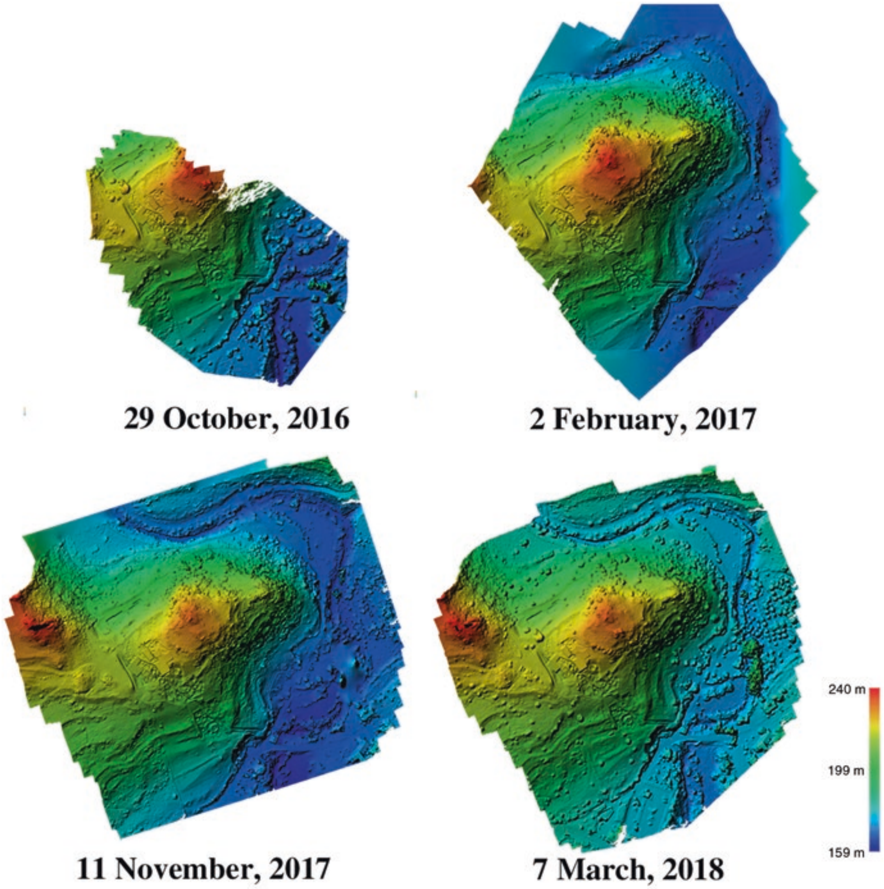


Fig. 12 DEM models of the Choirokoitia site

normal, lognormal, exponential, etc. The capability to simulate the effect of passive countermeasures, the dynamics of "flying rocks," and the effect of vegetation were implemented and tested against actual events (Frattini et al. 2012). A special elasto-viscoplastic strain-hardening model for impact on soft ground was also implemented (Di Prisco and Vecchiotti 2006). The results of the rockfall model were provided in both raster and vector formats and included rockfall frequency, fly height, rotational and translational velocity, and kinetic energy, as well as information about motion type and impact locations.

A digital elevation model (DEM) was provided by the Cyprus University of Technology to the University of Milano-Bicocca and was regenerated with a cell size of 1 m. Following the creation of contour lines with 1 m spacing, the vegetation present inside the DEM was deleted. Rockfall sources refer to the cells from which rockfall occur. Each source cell was given a positive integer value, which specified

Fig. 13 3 D model of the Choirokoitia site generated with UAV images

Table 1 Results of GNSS Control network

GPS station	Coordinates (LTM) lat/long	DE meters	DN meters	DU meters
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 number of the block that was simulated. For the study area, 100 blocks had been simulated from each cell. The source areas were mapped as a line beginning from a slope higher than 55 degrees, in accordance with the evidence of the ortho-photo with a resolution of 2 cm. All the simulated blocks are sphere with a density of

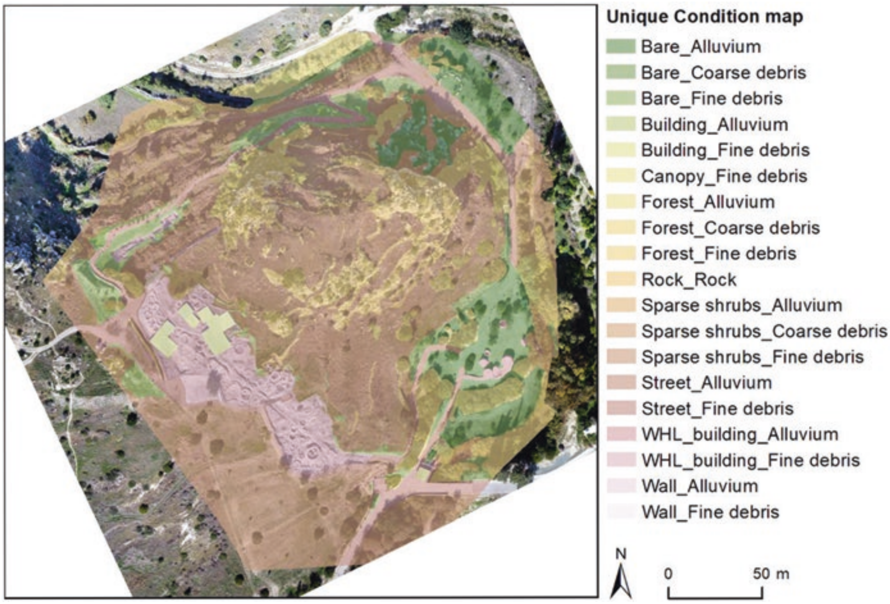


Fig. 14 Map of the land use and lithology for the Choirokoitia site

2700 kg/m^3. The area has been divided in two homogenous zones in accordance with the evidence from the available data. Two datasets have been created for each area through the mapping of blocks from the ortho-photo with 2 cm resolution, and as consequence, two volumes have been defined. In the HY- Stone software, the volumes are randomly sampled from a negative exponential distribution.

For each cell, the normal (En) and tangential (Et) restitution coefficients and rolling friction coefficient (tanr) parameters control the amount of energy lost by blocks at impact in normal and tangential direction and by rolling over the slope surface, respectively. The coefficients ranged from 0 (no restitution) to 1 (total restitution). Raster datasets tend to be derived in GIS by reclassifying maps of "unique condition units," which combined surface lithology and vegetation/land use derived through available data and photointerpretation (Fig. 14). In HY-Stone the variables are randomly sampled from a normal distribution, where the mean is corresponding to the parameter's reference value.

The results of the HY-Stone focused on the cumulative count of rockfall trajectories passing through each cell of the DEM. This represents a proxy of the probability of rockfall propagation or runout to a given location in the space. The calculations included the number of transit for each cell of the DEM and arrested location of the blocks on the slope, the kinetic energy distribution along the simulated trajectories, and the maximum values of blocks kinetic energy (J) for each cell of the DEM (Fig. 15). As is evident, the rockfall would occur on the east side of the Choirokoitia site (Valagussa et al. 2018).

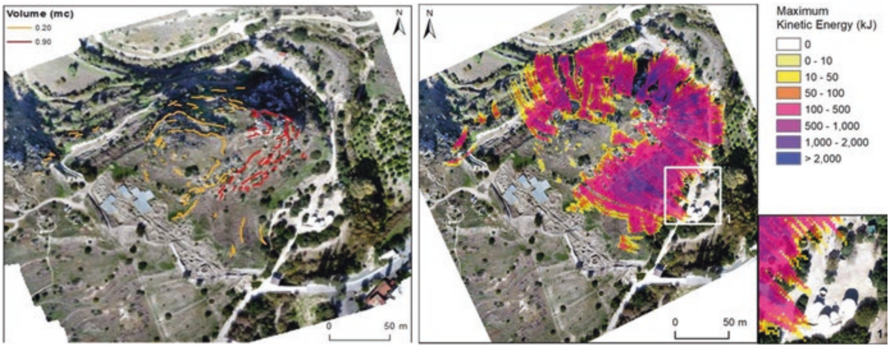


Fig. 15 Volume and values of kinetic energy (kJ) at the Choirokoitia site

Fig. 16 PSI Analysis of the Choirokoitia site (in white box) and the surrounding area

PSI Analysis

A PSI analysis was conducted at the Choirokoitia general area to determine any micro-movements in the area (Fig. 16). For the PSI analysis, 26 Cosmos Skymed SAR images from the years 2011–2017. For the dates defined, the points exhibit an average of 3.3 cm rate of movement per year (velocity). The archaeological site exhibits a rate of 0.24 mm and 0.11 mm for the two main targets identified within the site. Minor movement fluctuations (up to 4 mm) are also evident in the area for certain dates – these are often attributed to changes in temperature (expansion) or soil swelling due to the presence of water which also affects radar reflectivity (dielectric constant). 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.

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, and 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. The PSI analysis and GNSS control network of the Choirokoitia site showed a small displacement, which indicates the need for longer-term monitoring of the site to diagnose the severity of the geo-hazards. The rockfall modeling indicated a potential rockfall situation near the Choirokoitia site, which may endanger visitors to the site. Local-scale monitoring data is the base for the development of geological and geotechnical modeling 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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