Monitoring Cultural Heritage Sites Affected by Geohazards in Cyprus Using Earth Observation

Kyriacos Themistocleous

Abstract Monitoring geo-hazards of cultural heritage sites and structures as well as the surrounding archeo- landscapes facilitates the early recognition of potential risks and enables effective conservation, monitoring and planning. Landslides, earthquakes and erosion are the predominant geo-hazards in Cyprus. In order to identify and monitor geohazards and environmental displacements, Earth Observation techniques can be used in combination with long-term low-impact monitoring systems, such as UAVs and geodetic techniques to monitor and assess the risk from geohazards on cultural heritage sites and structures to evaluate potential changes and risks.

Keywords Cultural heritage · Geo-hazards · Earth observation monitoring

1 Introduction

Tangible cultural heritage sites are continuously impacted and weathered by several environmental factors, including climate change, precipitation, natural hazards, etc. (Themistocleous et al. 2016a; Agapiou et al. 2015, 2016; Margottini et al. 2016). Cultural heritage sites are highly vulnerable to geological disasters induced by earthquakes, volcanic activity, floods and catastrophic landslides, as well as non-catastrophic geo-hazards that can progressively affect its structural integrity and accessibility including slow-motion landslides, subsidence, sinkholes, ground settlement and active tectonics (Themistocleous 2018; Agapiou et al. 2015, 2016; Margottini et al. 2016; Themistocleous et al. 2016a). Several studies have focused on local-scale assessments of various geohazards on UNESCO World Heritage Sites (Howard 2013, Philips 2015, 2014; Howard et al. 2016; Wang 2015; Schmidt and Rudolff 2013; Lollino et al. 2015; Lanza 2003; Hapciuc et al. 2016; Vojinovic et al. 2016). Pavlova

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et al. (2017) identified 60% of the sites on the World Heritage list as being exposed to at least one geological disaster.

In order to examine the major risks to cultural heritage, it is vital to conduct a risk identification and assessment, which includes the history, topography, geology, land use, urban development and any other major risks that may affect the site. Although additional information regarding the geomorphological and geological processes of the area can improve understanding of the risk of natural hazards on cultural heritage sites (Howard 2013), most studies on long- term vulnerability studies on cultural heritage sites do not focus these variables (Tang et al. 2016). A recurring theme of studies on geo-hazards affecting cultural heritage sites is the need to strengthen monitoring and maintenance of vulnerable cultural heritage sites (Sesana et al. 2018). According to Tang et al. (2016), the adoption of combined structural and ground deformation monitoring methodologies facilitates the early recognition of potential risks that enables effective conservation planning. However, although deformation monitoring is essential for preserving significant cultural heritage sites, the published results are sparse (Gutiérrez and Cooper 2002; Rohn et al. 2005; Canuti et al. 2009).

Ecological risk assessment (ERA) can be used to assess the potential geo-hazards that are occurring at a specific cultural heritage site (UNESCO et al. 2010; Yanes et al. 2018). ERA focuses on the potential for producing a hazard and the vulnerability of exposure to a hazard (UNESCO et al. 2010). Therefore, the hazard is the external source of a disaster, and the vulnerability is the inherent weakness (UNESCO et al. 2010). To minimize these consequences and achieve sustainability, ERA can analyse potential and extreme adverse impacts that can be caused by geohazards, making ERA a powerful technical tool (Xu et al. 2015; Liu et al. 2018; Popescu et al. 2015).

In Cyprus, current infrastructure for monitoring and studying these natural hazards is limited to conventional equipment, such as seismographs, geophones, and inclinometers (Geological Survey Department). Thus, no systematic research has been conducted to monitor ground deformation with high accuracy and dense spatial resolution in a timely manner. Several geotechnical field investigations have been conducted by the Geological Survey Department (GSD) of Cyprus in collaboration with the British Geological Survey between 1985 and 1986 in Paphos District, and especially in the villages of Agios Photios, Kannaviou, Pendalia, and Simou, which are areas prone to landslides (Northmore et al. 1986; Northmore et al. 1988). Extensive research has been conducted to study several slope failures in Cyprus through extensive geological and geotechnical investigations as well as interpretation of aerial photographs and high- resolution satellite imagery for observation and verification of the results (Tzouvaras et al. 2020; Charalambous et al. 1997; Hart et al. 2010, 2013).

2 Types of Geohazards

CypruS is in an area of high susceptibility to seismic activities and landslides. The main geotechnical problems that take place are landslides, rock falls, ground subsidence, earthquakes and erosion, which pose serious disadvantages to the development of heritage sites and safety for tourism (Tzouvaras et al. 2020; Liu et al. 2019; Hagenlocher et al. 2018).

2.1 Landslides

Landslides are a major hazard in Cyprus, with large landslides taking place in the south-west part of the island, primarily in the Paphos district (Hart et al. 2013) as seen in Fig. 1. Extreme weather conditions such as drought and heavy rainfall can lead to amplification of the soil erosion processes (Tzouvaras et al. 2020).

In some parts of the Paphos District landslides cover as much as 70 per cent of the landscape. The landslides have been mapped by the Geological Survey Department of Cyprus in collaboration with BGS (Northmore et al. 1987; Northmore et al. 1988) and more recently as part of Scott Wilson's mapping programme. Figure 2 features the Digitized Locations of Landslides in Cyprus as developed by the Geological Survey Department of the Government of Cyprus.

Fig. 1 Landslide, Paphos-Limassol Highway in Cyprus

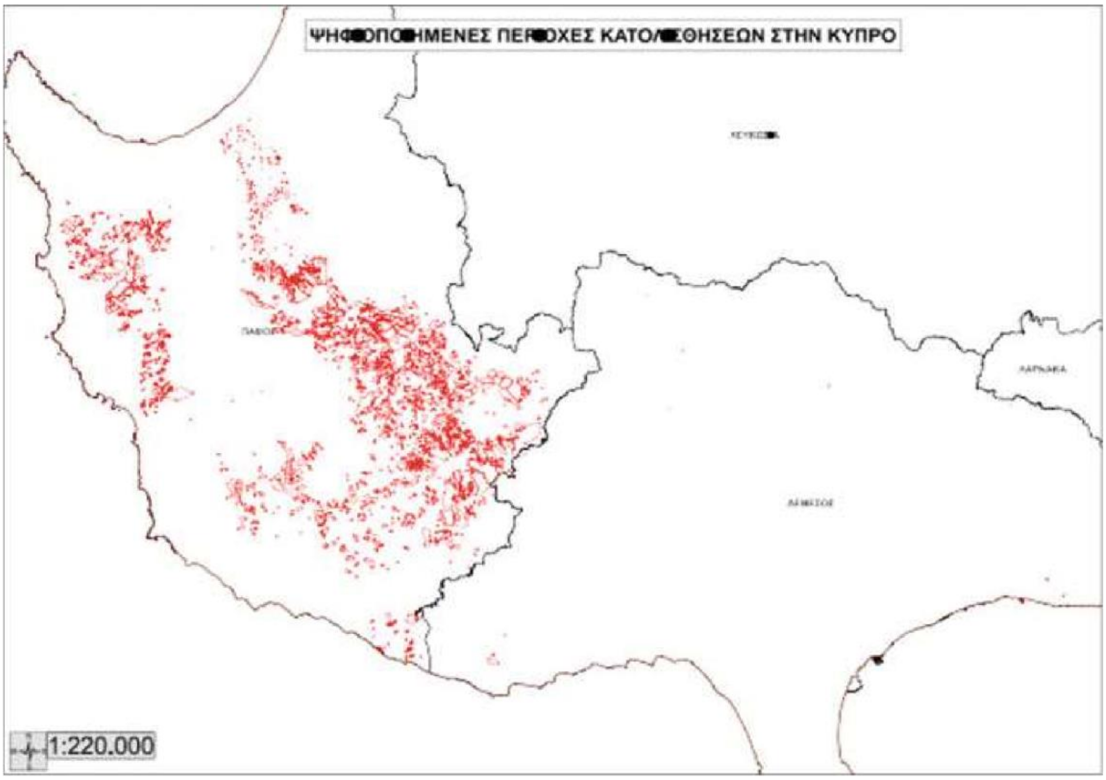


Fig. 2 Digitized Locations of Landslides in Cyprus (*Source* Geological Survey Department)

Landslides have resulted in significant damage to the Pissouri area in the southwest area in Cyprus (Fig. 3). The south western side of Cyprus has a long history of slope instability problems due to its morphological and hydrological conditions. Various factors have contributed to the current pattern of slope instability, such as climate change with intensive rainfall, hydrological conditions, land cover and land use changes (Tzouvaras et al. 2020). In this area, the remains of former sea-floor deposits and massive submarine slides, are exposed in the Paphos District situated between the Troodos Mountains and the sea. These deposits tend to be heavily deformed and are rich in the types of clay minerals that are prone to landslides (Tzouvaras et al. 2020). This tendency is exacerbated by the steep terrain and the long history of powerful earthquakes in the region (British Geological Survey). The terrain is characterised by steep-sided plateaux made up of 'Melange' and 'Kannaviou Clay' capped by thick chalk sequences.

Rockfalls are observed mostly in the mountainous areas of Cyprus and in natural and man-made slopes. They are mainly related to one or more causes of geological, topographical and rainfall conditions. Earthquakes often contribute to the fracturing of the rock mass and eventually to rock falls. Areas covered with loose deposits, including most of the coastal areas are more vulnerable to destruction in contrast to areas where the rocks are massive, like the Troodos range which is mostly covered with igneous rocks. Due to the nature of the main soil types in Cyprus ground which is composed of marls, clays, gypsum and sulfates, ground subsidence is a frequent phenomenon, as it is highly related to the geological conditions and the mechanical properties of the ground itself.

Fig. 3 Landslide in Pissouri area in Cyprus

2.2 *Seismic Hazards*

Cyprus is frequently affected by catastrophic earthquakes, as it lies within the Alpine-Himalayan seismic zone, in which about 15% of the world earthquakes occur (Cagnan and Tanircan 2009). The entire island is considered an earthquake vulnerable area. The seismicity of Cyprus is thought to be due to the "Cyprus Arc", which constitutes the tectonic boundary between the African and Eurasian lithospheric plates in the region, which is situated in the sea to the west and south of Cyprus (Mart and Ryan 2002). Between 1896–2004, more than 400 earthquakes occurred which had their epicentres on Cyprus. As seen in Fig. 4, most earthquakes have their epicentres in the west and south, which affects the coastal areas in the western and southern areas of the island. A large number of medium to strong earthquakes have their epicentres in the sea, several tens of kilometres away from inhabited areas and the damage that may cause is small to negligible, as the intensity with which an area is struck depends on the epicentral distance.

2.3 *Erosion*

In Cyprus, extreme weather conditions such as drought and heavy rainfall can lead to amplification of erosion processes. Rocks eroded through physical erosion often form clastic sediments. Clastic sediments are composed of fragments of older rocks that have been transported from their place of origin (National Geographic 2020). Softer stones such as limestone and soapstone are eroded much more quickly (Sensana et al.

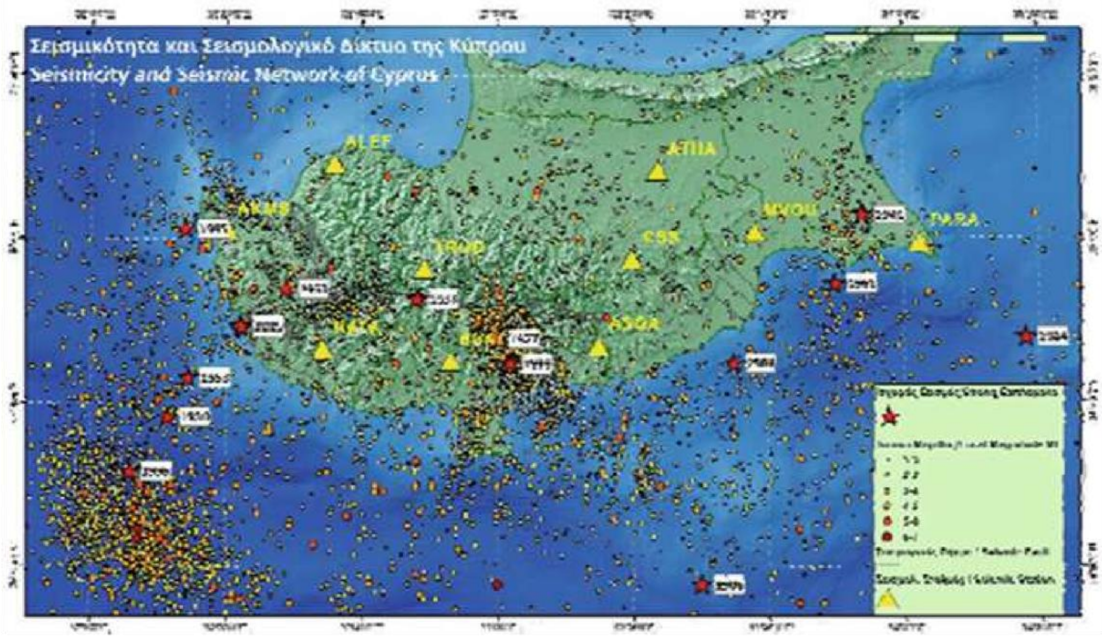


Fig. 4 The Seismicity of Cyprus up to 2018 (*Source* Department of Geological Survey 2018)

2018). Changes in atmospheric acidity, landform development, and vegetation cover rapidly affect the intensity and rate of the erosion process (Fig. 5).

Stone weathering has been investigated on several stone monuments, including studies on the on-going weathering rate are especially effective to evaluate the present condition of stone monuments in order to identify the extent of erosion on the cultural heritage site (Doehne and Price 2010; Winkler 1986). To understand the present weathering condition of target monuments, the first step is to measure the precise shape of the stone surfaces. Erosion rates on rocks can be obtained easily since most stone-built cultural heritages sites tend to have a geometrical shape. As well, such sites are more commonly located in humid temperate areas. North-facing surfaces tend to have lower rates of erosion than surfaces facing in other directions because each surface has different temperature and moisture conditions due to insolation.

Coastal sites have long been a significant focus of archaeological research, particularly in the Mediterranean (Knapp and Demesticha 2017). Several ancient civilizations have existed in the Mediterranean area (Canzenave 2014; Benoit and Comeau 2005; EEA 2014), resulting in a high concentration of cultural heritage sites in the Mediterranean coastal areas. Despite recent theoretical and methodological advances in coastal archaeology, on-going erosion remains a serious predicament for both the preservation and interpretation of coastal sites.

The coastal zone of Cyprus is a valuable and vulnerable area. This zone, in which most urban development and economic activity takes place, covers 23% of the total country's area, 50% of total population and 90% of the tourism industry (EU 2018). According the European Commission's report on climate change in Cyprus, 30% of the coastline under control of the Republic of Cyprus is subject to erosion (EU 2018; Papadaskalopoulou 2014). 38% of the coastline is already subject to erosion, mostly

Fig. 5 Erosion in the Tomb of the Kings region, Paphos (*Source* A photograph taken by Kyriacos Themistocleous in 2017)

the result of human activities such as beach mining, dam and illegal breakwater construction and urbanization (EU 2018).

South-central Cyprus is experiencing the highest rates of coastal erosion on the island (EU 2018; Papadaskalopoulou 2014). Although archaeological sites in this region have received increased attention as a result of systematic surveys (Manning et al. 1994; Manning et al. 2000; Georgiou 2013; Andreou and Sewell 2015; Demesticha 2015), the impact of coastal erosion has only recently been investigated from a cultural heritage perspective (Andreou et al. 2017). Studies such as the Cyprus Ancient Shoreline Project (CASP) are focused on monitoring the impact of coastal erosion on archaeological sites (Andreou 2018). Since 2014, the CASP has compiled archaeological and geographical information through aerial photographs to reconstruct historical coastlines in this region digitally, and to map sites that are under threat. More recently, this dataset was examined to classify the severity of coastal erosion, and to highlight the areas that require more frequent recording (Thieler et al. 2009; Radosavljevic et al. 2016; O'Rourke 2017).

3 The Case Study of Choirokoitia, Cyprus

The documentation site is the UNESCO World Heritage Site of Choirokoitia in Cyprus (Fig. 6). The Neolithic settlement of Choirokoitia is considered one of the most important prehistoric sites in the Eastern Mediterranean (UNESCO n.d.) as it is one of the best-preserved settlements of this period in Cyprus and the Eastern Mediterranean. The Neolithic settlement of Choirokoitia is located in the District of Larnaka, 6 km from the southern coast of Cyprus and lies on the slopes of a hill.

The site, which was occupied from the 7th to the 5th millennium B.C., is a village that covers an area of approximately 3 ha at its maximum extent. The site is an example of the Aceramic Neolithic period in of Cyprus at its pinnacle, where the first organized human community was developed. The site was initially.

populated by farmers originating from the Near East mainland around the beginning of the 9th millennium.

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 (Fig. 7). According to UNESCO, the site was officially abandoned in the 4th millennium BC. The reason for this abandonment remains unknown (UNESCO n.d.).

Fig. 6 Aerial photo of the Choirokoitia, Cyprus

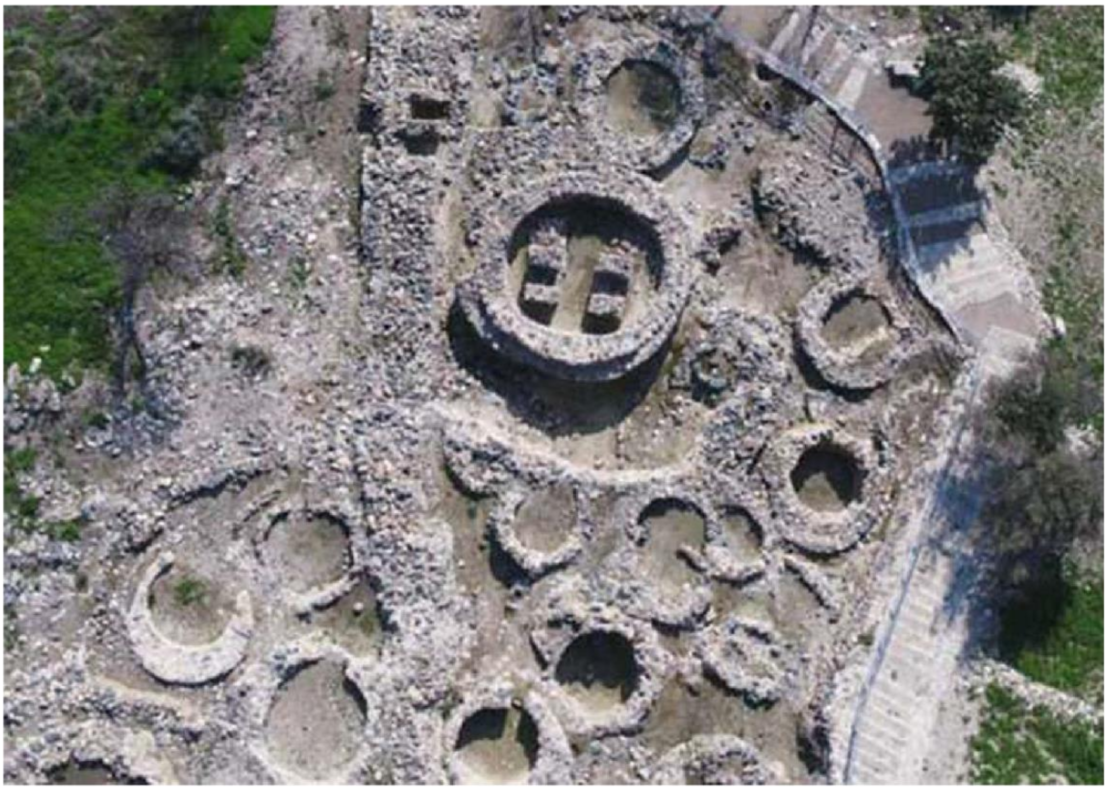


Fig. 7 Excavated houses in Choirokoitia

3.1 Methods

In order to identify and monitor geo-hazards and their severity, local scale monitoring is used. Local scale monitoring provides the opportunity to identify deformation phenomena resulting from geo-hazards for monitoring, assessing and predicting geo-hazards using field survey techniques to measure and document the extent of damage on the cultural heritage site. This method integrates field monitoring techniques such as UAVs, laser scanning, total stations and GPS as well as satellite techniques such as InSar data (Margottini et al. 2015, 2018; Novellino et al. 2018; Themistocleous 2017; Themistocleous et al. 2017a).

Monitoring cultural heritage sites and monuments in Europe has traditionally used on-site observation. However, this procedure can be time consuming, difficult and expensive, especially in large or remote areas, since it includes periodical observations, field surveying and ground-based data collection (Themistocleous et al. 2016a). Deformation monitoring in cultural heritage sites is often 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 (Zhou et al. 2015; Garziera et al. 2007; Glisic and Inaudi 2008). However, such methods can only acquire data of the monitored structure within the cultural heritage sites and does not include the entire area of the site and its surrounding landscape (Zhou et al. 2015). Moreover, the installation of monitoring devices, such as optical targets, permanent GNSS stations or inclinometers, on the heritage sites and monuments can affect the integrity the heritage site.

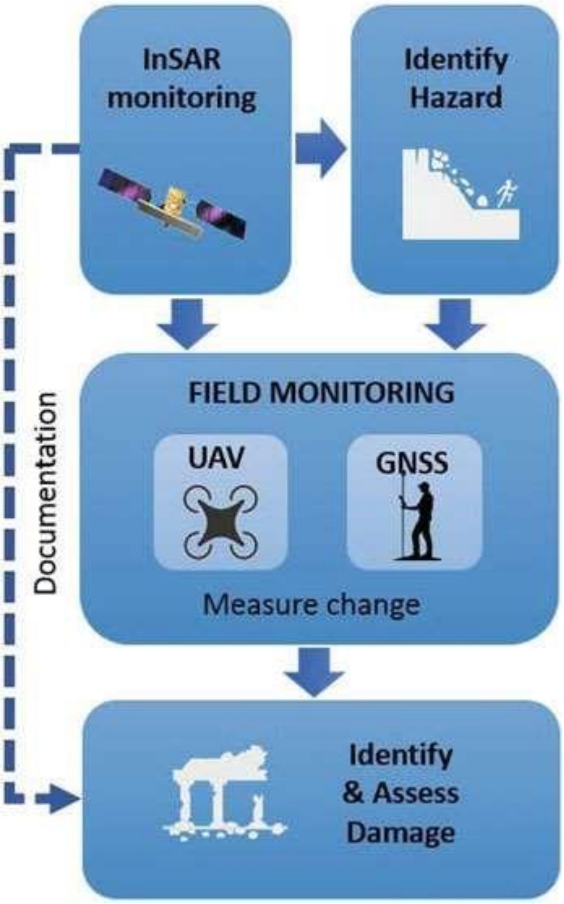
Space-based Earth Observation (EO) monitoring techniques can be used to identify natural hazards (Casagli et al. 2016). Research indicates that the integration of satellite data and in-situ data offers the best solution for monitoring geo-hazards in cultural heritage sites (Margottini et al. 2015, 2018; Novellino et al. 2018). Local scale monitoring can be used to assess the severity of these geo-hazards by using integrated field monitoring techniques while satellite radar interferometry is capable of monitoring surface deformation with high accuracy using precise ground measurements. Once cultural heritage sites vulnerable to geo-hazards are identified using InSAR satellite imagery, local-scale monitoring can be used to assess the severity and monitor the cultural heritage sites over time. Ground-based geotechnical monitoring and surveying models are used to measure deformation parameters (e.g. strain and inclination) over a relatively short measurement base. In-situ measurements using UAV and GPS are then used to measure possible movements that may result from geo-hazards (Themistocleous 2017a, b, Gikas 2012; Themistocleous 2017) Field monitoring can be combined with UAVs for documentation purposes and 3D modeling comparison. The aerial imagery obtained from UAVs can be processed using photogrammetry methods, such as Structure in Motion to generate highly accurate point cloud models in order to document and monitor the extent of progressing geo-hazards. In this way, areas exposed to geo-hazards and their evolution over time can be monitored and crucial information can be provided to decision makers in order to protect cultural and heritage sites from natural hazards.

3.2 Methodology

A methodology for local-scale monitoring of cultural heritage sites was developed during the PROTHEGO study that would assess the risk from natural hazards on the archaeological sites and monuments from a geospatial perspective (Fig. 8) (Margottini et al. 2016, 2018; Themistocleous et al. 2017a). A multi-criteria analysis of the UNESCO sites was conducted to estimate the severity of each geo- hazard (Silvestrou and Themistocleous 2018). The main objective of the methodology was the development of 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 et al. 2016a; Themistocleous 2018a).

In order to test the PROTHEGO study, the methodology developed was applied to the Choirokoitia World Heritage site in Cyprus to assess the risk from geo- hazards on the archaeological sites and monuments from a geospatial perspective. The methodology focused on long-term, low-impact monitoring systems as well as indirect analysis of environmental context to investigate changes and decay of a structure or landscape (Themistocleous et al. 2016b). The methodology for the local scale monitoring begins with the use of InSAR images to identify natural hazards in the UNESCO World Heritage demonstration sites. When InSAR ground motion data indicates that

Fig. 8 PROTHEGO methodology



a geo-hazard is evident at or near the demonstration site, field monitoring and verification is used to document and measure the extent of change caused by the natural and/or geo-hazards, if any. Documentation of the damage can be performed, using UAVs and photogrammetry.

A GNSS network was established at the Choirokoitia site in order to monitor the site from ground displacement (Fig. 9). The geodetic network consisted of four points in total. The main control point was established on solid ground outside the area of interest, whilst the remaining three points were set up in carefully selected locations (i.e. on top of rocks or ridge lines) after consulting geologists and archaeologists to address high-risk areas within the site.

Two types of GNSS receivers were used for data acquisition; (a) 3 Trimble R9s equipped with Zephyr 2 Geodetic GNSS antennas, and a Leica GS15 Smart GNSS receiver were used to monitor displacement using satellite (GNSS) and combined with conventional techniques (via high precision total stations and levels) to identify potential ground displacements with respect to the network reference points, during the life-span of the monitoring activity. Horizontal displacements were measured using an industrial-grade total station (Topcon® MS05AXII), which bears nominal accuracy in directions and ranges of 0.5″ and 0.5 mm respectively when combined with specifically designed topographic prisms and reflective targets. Vertical motion was measured using a high-precision digital level (Leica Geosystems® DNA03). The

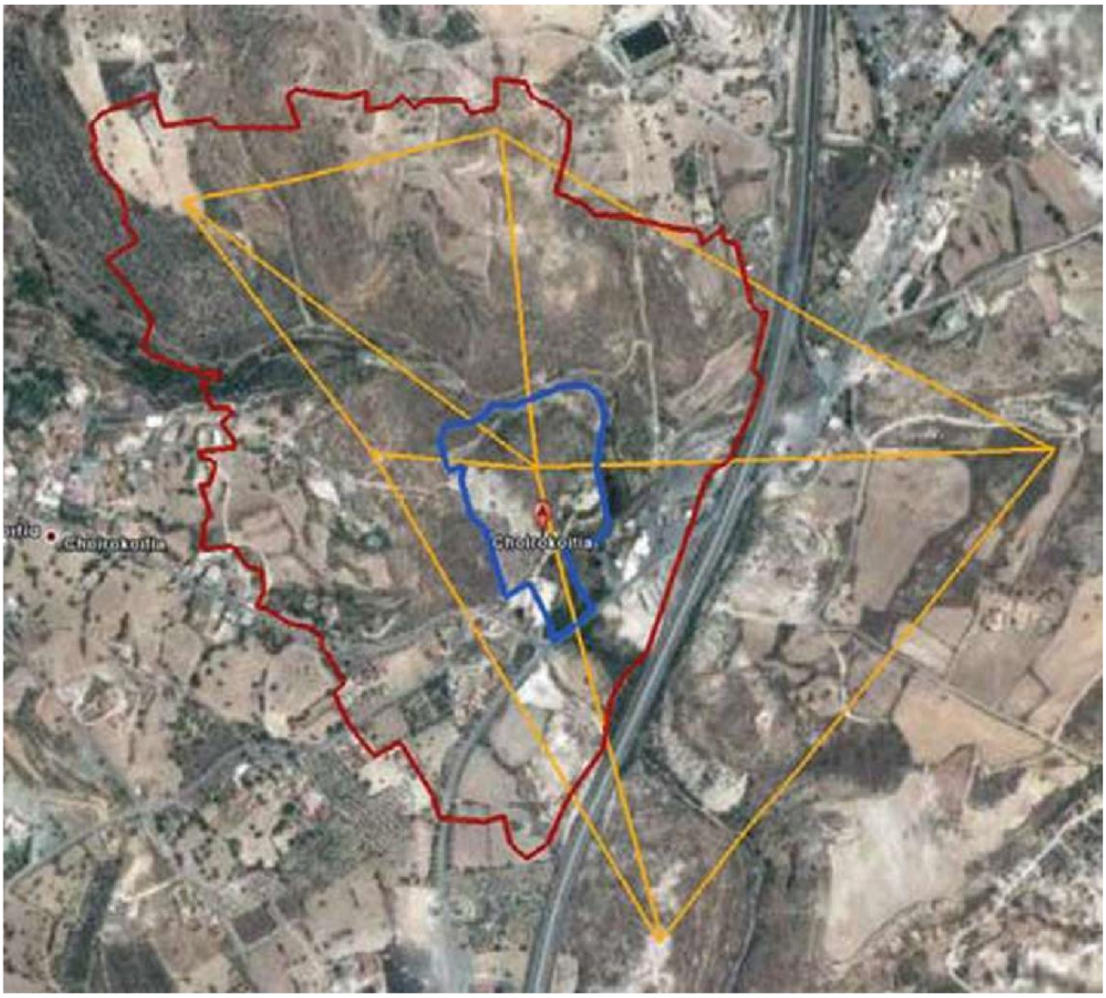


Fig. 9 Geodetic Network at the Choirokoitia area

leveling campaign were carried out using Invar Barcode Staffs, achieving a vertical accuracy at the order of 0.3 mm/km. 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 (Themistocleous et al. 2018b).

Images generated from UAVs are used to document cultural heritage sites under threat from geo-hazards (Fig. 10). Hundred of UAV images are used to create orthophotos, dense point clouds, 3D model and Digital Elevation Models (Themistocleous 2017). It is recommended that UAVs be equipped with a high- resolution camera to acquire images over a site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-image and point.

Fig. 10 UAV flight over Choirokoitia area

3.3 Results

To support field monitoring, geometric documentation of the area was performed using RTK GPS measurements (ground control points) with images taken by UAV systems and processed using photogrammetry techniques. This data was supported and geo-referenced using a geodetic network measured via contemporary GPS/GNSS receivers by reconstructing the cross-sections over the identified areas of the site in order to investigate possible changes in the vertical and horizontal profiles of the cultural heritage site. As part of the local-scale monitoring process of the Choirokoitia demonstration site, a UAV fitted with a 20 MP camera was used to acquire images of the Choirokoitia site over the course of 13 months that were processed using photogrammetry to produce Digital Elevation Models (DEM) and ortho-images for comparison over temporal intervals (Themistocleous 2019).

The digital images acquired by the UAV flight were interpolated in order to create high resolution, scaled, geo-referenced 3D model based on photogrammetric techniques. Using images from the UAV flights ortho- photos were created. Following the generation of point clouds from the UAV images using a distribution of ground control points (GCP) throughout the site, the model had sub-centimeter accuracy, which was critical in order to compare the 3D model with the GNSS measurements.

Following, Digital Elevation Models (DEMs) (Fig. 11) and Elevation Contour Maps were generated to examine changes and deformation in the Choirokoitia cultural heritage site over time. The DEMs were generated from the images acquired from the UAV were processed based on the position of the GCPs and compare the results with the GNSS measurements and the InSAR images. During the 13-month monitoring period, all the measurements were recorded and showed a slight shift at the top peak of the hill, at the PILR.

During the two GPS/GNSS campaigns of the geodetic network in the area of interest within a 5-month period, GNSS observations of 1 Hz were collected for a timespan of six hours. The four GNSS network points were measured to compute displacement in the East (DE), North (DN) and Up (DU) directions. The displacements were derived from topocentric coordinates with respect to the main network control point. The results of the GPS/GNSS campaigns indicate a change of 2 cm in

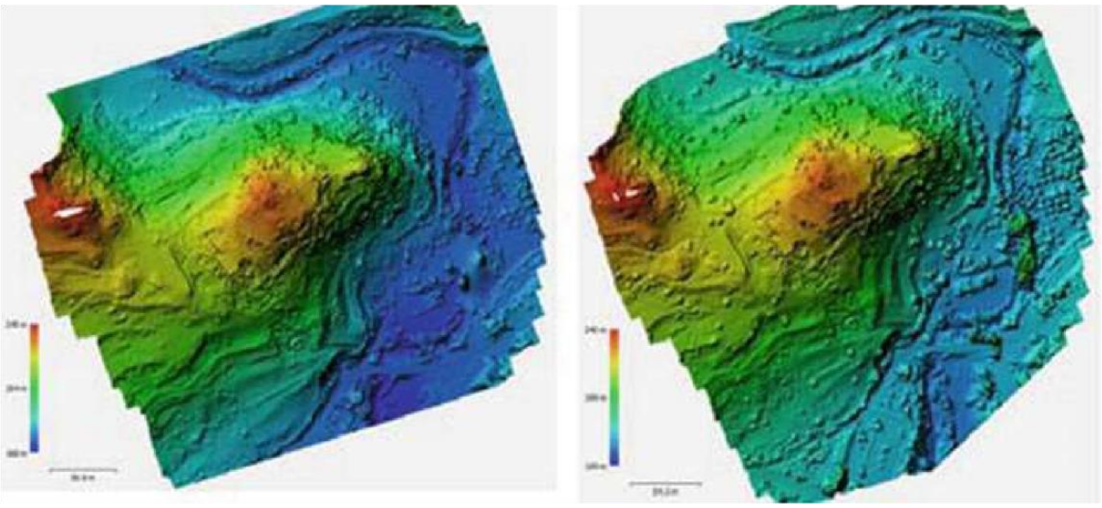


Fig. 11 DEM of Choirokoitia site 11/11/2017 and 7/3/2018

the Up component (vertical) within the 5- month period. Furthermore, a PSI (Persistent Scatterer Interferometry) analysis was conducted on the Choirokoitia broader area to determine potential displacements using 26 Cosmos Skymed SAR images from the years 2011–2017. During this time span, the points exhibit an average velocity of 3.3 cm per year. The results of the PSI analysis reveal a similar displacement pattern at the broader area occupied by the GNSS control network. As well, a displacement of 2 cm was identified using a UAV model cross section comparison for the UAV images generated from 2.

February 2017 until 11 November 2017 feature. Longer- term monitoring of the cultural heritage site is required in order to identify and correlate the two techniques and measure and monitor the severity of the displacements (Fig. 12).

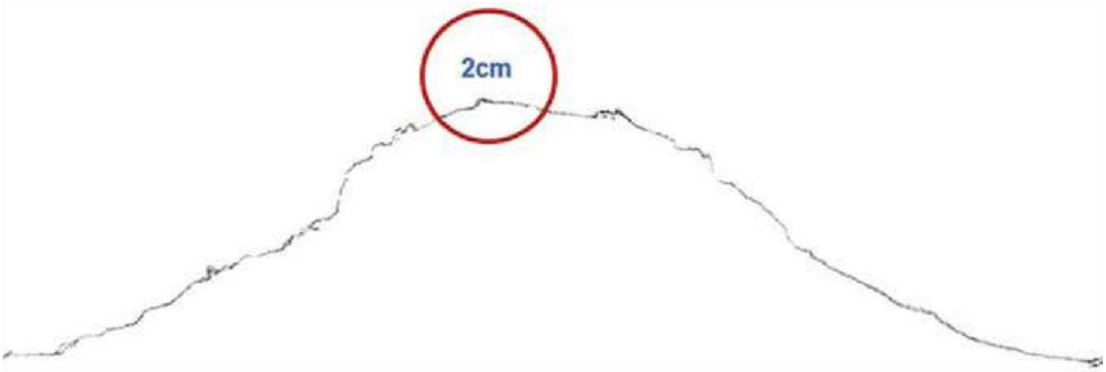


Fig. 12 UAV model comparison of displacement (*Source* An image created by Kyriacos Themistocleous in 2019)

4 Conclusions

The case study at Choirokoitia, Cyprus provides an example of detecting and analyzing geo-hazard induced ground deformation based on InSAR ground motion data and field survey techniques for cultural heritage applications. InSAR data, satellite positioning and conventional surveying techniques were employed to measure the micro-movements, while the UAV and photogrammetry were used for documentation purposes and 3D modeling comparisons. A correlation is evident between the geodetic techniques and SAR images, as the PSI analysis and GNSS Control Network of the Choirokoitia site exhibited similar levels of displacement suggesting that longer-term monitoring of the site is required to diagnose the severity of the problem. Furthermore, local-scale monitoring data forms the basis for the development of geological and geotechnical models of the kinematics of the investigated sites. Such information can provide detailed models highlighting the evolution of deformation processes affecting the heritage sites and thereby identifying the best mitigation strategy and to evaluate the effectiveness of these actions for the test site. Future research can further develop the methodology for identifying geo-hazards by using multi- sensor co-located configurations, including permanent GNSS reference stations, weather stations, tiltmeters as well as specifically designed Corner Reflectors established throughout Cyprus to estimate deformation with dense spatial resolution at the cm- to mm-level using corner reflectors. This will enable effective and accurate surveillance of geo-hazards, which can be used to provide early warning services, risk management, and mitigation of the impact of natural hazards on cultural natural heritage sites. In addition, Ecological risk assessment can be used to provide a model of the vulnerability of the cultural heritage site as well as the severity of the impact of geo-hazards on the site.

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