Monitoring ground deformation of cultural heritage sites using SAR and geodetic techniques: the case study of Choirokoitia, Cyprus

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ABSTRACT
Nowadays, assessing geo-hazards in cultural heritage sites in most cases takes place after the hazard has occurred. Monitoring structural and ground deformation resulting from geo-hazards facilitates the early recognition of potential risks and encourages effective conservation planning. This paper presents an integrated ground deformation monitoring approach based on the combined use of Satellite SAR data, campaign-based GPS/GNSS observations and aerial images from UAVs within the Choirokoitia UNESCO World Heritage Site in Cyprus. The Neolithic settlement of Choirokoitia is one of the most important prehistoric sites in the eastern Mediterranean. The site is located on a steep hill, which makes it vulnerable to rock falls and landslides. As part of the PROTHEGO project, a series of field measurements were collected at the Choirokoitia site and compared against Satellite SAR data to verify kinematic behavior of the broader area and to assist in monitoring potential geohazards over time. The results obtained indicate displacement rates of the order of 0.03 m/year. These results indicate that ground deformation should be monitored in the area surrounding the Choirokoitia using long-term, low-impact monitoring systems such as SAR images, UAV-based and geodetic techniques. The combination of such monitoring technologies can be compared to monitor and assess potential geo-hazards on archaeological sites with increased accuracy.

I. Introduction

Cultural heritage is 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, sinkholes, ground settlement and active tectonics (Pavlova *et al*, 2017, Hu *et al*, 2019; Klimes, 2013; Chen; 2012; Parisi & Augenti, 2013; Gikas et al, 2009). Deformation monitoring is essential for preserving significant cultural heritage sites, the published results are sparse (Gutiérrez & Cooper, 2002; Rohn *et al*, 2005; Canuti *et al*, 2009). Long-term vulnerability studies of the cultural heritage usually focus on the actual structure in response to environmental risks, such as the degradation and corrosion of building materials (Brimblecombe, 2000, Fort *et al*, 2006), without fully considering the entire geological and geotechnical setting. Currently, assessing geo-hazards in cultural heritage sites takes place after the geo-hazard has occurred. However, the high costs associated with the maintenance of cultural heritage sites directly enforce the prioritization of the monitoring and conservation policies that necessitate to ensure sustainable conservation. In response, the adoption of combined structural and ground deformation monitoring schemes facilitates the early recognition of potential risks that enables effective conservation planning (Tang *et al*,2016, Pavlova *et al*, 2017, Pastonchi *et al*, 2018).

On-site observation has been the most widely adopted way of monitoring cultural heritage sites and monuments in Europe. However, this procedure relies on field surveying and ground-based measurement, which can be time-consuming and expensive especially over large or remote areas. (Themistocleous *et al*, 2016a). Deformation monitoring in cultural heritage sites is usually carried out by installing GNSS units in or around 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 & Inaudi, 2008). However, such methods can only acquire monitoring data of the actual structures within a cultural heritage site, thereby ignoring the entire broader area and the 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 lead to aesthetic and functional impacts that can affect the integrity and accessibility of the area.

The PROTHEGO project (www.prothego.eu) sought to develop and validate an innovative and multi-scale methodology for identifying and monitoring of European Cultural Heritages exposed to natural hazards, namely monuments, structures and archaeolandscapes that are potentially un-stable due to landslides, sinkholes, ground settlement and active tectonics a, all of which could be affected by climate change and human interaction. PROTHEGO sought to develop 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 (Margottini *et al*, 2016; Themistocleous, 2017). Afterwards, the CyCLOPs project continued the study of geohazards in order to establish of a novel strategic research infrastructure unit for monitoring solid earth processes and geohazards in Cyprus. A network deployment of permanent multi-sensor configurations (Tier-1 GPS/GNSS reference stations, SAR Corner Reflectors, weather stations, tiltmeters) throughout Cyprus and will be used to promote geohazard monitoring, critical infrastructure resilience and enhance national geodetic and spatial data infrastructure. These activities will be further incorporated and further developed under the auspices of the EXCELSIOR project, which is developing a Center of Excellence that will focus on Earth observation monitoring in Cyprus and the EMMENA region.

II. Study Area

The study area is the UNESCO World Heritage Site of Choirokoitia in Cyprus. The Neolithic settlement of Choirokoitia is one of the most important prehistoric sites in the Eastern Mediterranean (UNESCO) and has been 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, 6 km from the southern coast of Cyprus, the Neolithic settlement of Choirokoitia lies on the slopes of a hill, partly enclosed by the Maroni River. 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 settlement remains have been excavated which were constructed with limestone, clay and brick. According to UNESCO, the site was officially abandoned in the 4th millennium BC. The reason for this abandonment remains unknown (UNESCO).

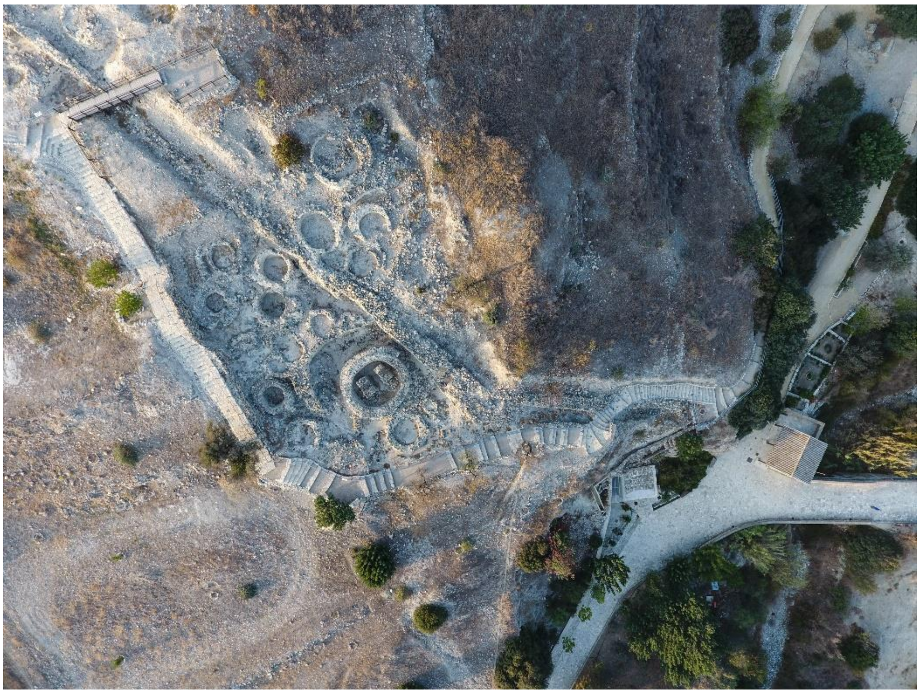

Fig 1. Neolithic settlement of Choirokoitia site (add map)

The geology of the area is characterized mostly by fine debris, coarse debris, rocks and alluvium around the site.

III. Monitoring geo-hazards

According to Margottini *et al*, (2015), 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. Once vulnerable sites are identified by Interferometric Synthetic Aperture Radar (InSAR) satellite imagery, local-scale monitoring and advanced modeling can be used to monitor the cultural heritage sites over time. Local scale monitoring methods, which may include in-situ observations and remote sensing techniques such as Permanent Scatterer (PS) techniques, can be used to validate the impact of natural hazards. Topographic surveying using differential Global Navigation Satellite System (GNSS), images from Unmanned Aerial Vehicles (UAVs), photogrammetry and InSAR data can be used to monitor slow ground movements, which can be compared and validated with ground based geotechnical monitoring in order to evaluate the extent of damage within cultural heritage sites resulting from geo-hazards and to monitor the changes to the site 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 so they can decide what actions need to be taken in order to protect cultural and heritage sites from geo-hazards.

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. Geodetic GNSS techniques can be used in combination with UAVs for documentation purposes and 3D modeling comparison. The aerial imagery obtained from UAVs can be processed using photogrammetry methods, such as Structure from Motion (SfM) to generate highly accurate point cloud models in order to document and monitor the extent of progressing geo-hazards. Ground-based geotechnical monitoring and surveying models can then be compared and validated with InSAR data to evaluate cultural heritage sites deformation trends. 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 with conventional surveying offers the best solution for monitoring geo-hazards in cultural heritage sites (Margottini *et al*, 2015; Novellino *et al*, 2018; Margottini *et al*, 2018; Hu *et al*, 2019). Geotechnical techniques are used to measure deformation parameters (e.g. strain and inclination) over a relatively short measurement base. In-situ measurements using UAVs, total stations, laser scanning and GPS/GNSS are also used to enhance geo-hazard monitoring. (Gikas 2012; Themistocleous 2017).

A. ***SAR Images***

By examining regions of interest above the Earth's surface, Synthetic Aperture Radar (SAR) imaging satellites, Interferometric SAR (InSAR) and Persistent Scatterer Interferometry (PSI) processing techniques (Rosen *et al*, 2000; Ferretti *et al*, 2011; Crosetto *et al*, 2010; Pastonchi *et al*, 2018) can be used for estimating, with up to centimetre precision, subtle and non-catastrophic long-term and seasonal land processes. Such processes are triggered by a variety of natural and anthropogenic causes and drivers that can cause damage to the tangible heritage. Once vulnerable sites are identified by InSAR, detailed geological interpretation, hazard analysis, local-scale monitoring, advanced modeling and field surveying for the most critical sites will be carried out to discover possible cause and extent of the observed motions.

SAR images, acquired using active radar sensors, are processed with multi-interferogram methods, such as the Persistent Scatterers (PS), can be used to extract information on ground displacement that occurred across the areas of interest during the monitoring period, thereby providing an effective solution to measure large-scale surface deformations from space (Zhou *et al*, 2015; Ferretti *et al*, 2011; Hooper *et al*, 2012; Chen *et al*, 2013; Chen *et al*, 2012). Differential Interferometric SAR (InSAR) methods combine the radar returns from two or more radar scenes over the same area to detect changes that occurred between subsequent acquisitions with precision up to millimeter level, allowing for the monitoring of even subtle ground movements – down to a few centimetre – across wide areas (Chen *et al*, 2015; Zhou *et al* , 2013; Evans & Farr, 2007; Polcari *et al*, 2015). Research indicates that SAR data can provide powerful information for archaeological investigations including archaeological landscapes, site detection, change detection and structural monitoring (Lasaponara & Masini, 2013; Pastonchi et al, 2018). However, the spatial coverage of satellite data is limited by the SAR imaging geometry caused by layover, foreshortening and shadowing effects (Ferretti *et al*, 2001).

The Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) technique is used in remote sensing as a method for monitoring ground displacements induced by geohazards and anthropogenic phenomena. Persistent Scatterers Interferometry (PSI) has the capability to measure ground deformations with a millimetric resolution and to overcome the effects of natural decorrelation and atmosphere. The technique is suitable for measuring the gradual movement over relatively flat terrain and for slope stability monitoring if movement is either creeping or moderate movement (on the order of <10cm/year). The technique uses a stack of SAR interferograms and determines the motion history for pixels that are identified to have temporal phase stability. The exact position of naturally occurring PS is generally not known and it is therefore useful to have targets with known position distributed throughout the area of interest that can be used to validate PSInSAR with other geodetic observations. PSI is performed by utilizing fixed targets, often called point scatterers (PS), such as buildings, outcrops or other man-made structures. 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. In remote areas these interferometric outputs can be compared with in-situ measurements (GPS, levelling, inclinometers) and used as initial input for any geotechnical modelling.

B. ***Imagery from Unmanned Aerial Vehicles (UAVs)***

In recent years UAVs have been used extensively in cultural heritage and archaeological research as they provide higher resolution images compared with satellite imagery ones. Remote sensing technologies on UAV platforms are extremely useful for the detection and monitoring of cultural heritage (Baiocchi *et al* 2019; Themistocleous, 2017; Agapiou *et al*, 2013). UAVs can be an efficient, non-evasive and low cost resource to document cultural heritage sites (Themistocleous, 2017; Agapiou *et al*, 2013; Ahmadabadian at al, 2013) and can be equipped with sensors that enable the production of an unprecedented volume of high-resolution, geo-tagged image-sets of cultural heritage sites (Kostrzewa *et al*, 2003; Ruffino & Moccia, 2015; Scholtz *et al*, 2011). Moreover, UAVs provide an inexpensive and effective method for mapping cultural heritage sites, thereby providing a more efficient and more sustainable approach to documentation of cultural heritage sites (Themistocleous, 2017, Lo Brutto *et al*, 2014; Burkhart *et al*, 2014; Colomina & Molina, 2014). Recent developments in photogrammetry provide an affordable method for generating relatively accurate 3D models from 2D images (Ioannides *et al*, 2013; Themistocleous *et al*, 2015b; Al-Ruzouq, 2012). To document cultural heritage sites under threat from geo-hazards, UAV images can be used to create ortho-photos, dense clouds, 3D model and Digital Elevation Models (Themistocleous, 2017; Bitelli *et al*, 2019;

Apollonio *et al*, 2014; Al-Ruzouq, 2012). The UAVs are equipped with digital cameras to acquire images over the site with fixed ground control points in order to geo-reference the images and to generate a high accuracy ortho-image and a 3D point cloud model using photogrammetry.

In order to utilize the UAV images, it is necessary to position and measure Ground Control Points (GCPs) over the entire area prior to the flight (Baiocchi *et al*,2019) in order to make the necessary corrections during the post-processing of the images. The coordinates of the GCPs points are usually surveyed with a double frequency GPS system with estimated accuracy of less than 2cm. Flight planning software is used with the UAV to create a pre-determined flight path, thus ensuring significant image coverage and overlap for generation of stereo-pairs of images. In archaeological settings, the images should have at least an 80% overlap within each image in order to correct distortions and create an accurate 3-D model using photogrammetry.

The goal of photogrammetry is the measurement of the position of a set of 3D points, while the computer vision aimed at the final appearance of the model (Aicardi *et al*, 2017). Photogrammetry offers a rapid and accurate method of acquiring three-dimensional information regarding cultural monuments (Al-Ruzouq, 2012). This made the use of image-based approaches for 3D models reconstruction enormously increase, which is an essential part of the cultural heritage documentation and analysis processes (Aicardi *et al*, 2017). The aerial imagery obtained from UAVs can be processed using photogrammetry methods, such as Structure from Motion (SfM), to generate highly accurate point cloud models in order to document and monitor the extent of progressing geo-hazards. Software such as Agisoft PhotoScan Professional allow the generation of high resolution georeferenced orthomosaic exceptionally detailed DTMs and textured polygonal models using image overlay (Eisenbeiss, 2009). It is capable of interpolating digital images in order to create high resolution, scaled and georeferenced 3-D models from them. All images can be included in processing or it is possible to select a sub-set of images on key sites with the study area for more detailed analysis ensuring sufficient overlap and GCPs allow for this. The first step in the program's procedure is SfM. At this stage the software analyses the dataset, detecting geometrical patterns in order to reconstruct the virtual positions of the cameras that were used. The second step involves the creation of a complete geometry of the scene using a dense multi-view stereo reconstruction. At this stage the dataset of images are employed to produce a high-resolution geometry of the surface. This step successfully creates a 3D model, also known as a Digital Surface Model (DSM). Agisoft PhotoScan Professional's set of functions include aerial triangulation, polygonal model generation (plain/textured), setting coordinate system, georeferenced DTM generation and georeferenced orthomosaic generation. The fully automated workflow enables a non-specialist to process hundreds of aerial images on a desktop computer and to produce professional class photogrammetric data. To complete the georeferencing task, the program requires either GPS coordinates associated with cameras, provided in an EXIF / plain text file or in this case by ACPs generated by the autopilot, or GCP coordinates that can be used to achieve higher accuracy.

C. *Geodetic Techniques*

For local-scale monitoring needs, surveying techniques are used to determine the absolute positions and displacements at selected locations of the earth surface, while geotechnical techniques are employed to measure deformation resulting from geo-hazards over a relatively short measurement base and underground. Surveying techniques, such as total stations, leveling, and Global Navigation Satellite Systems (GNSS) surveying systems are used to measure the positional changes in a specific area at cm to mm level accuracy. They have also been successfully used for measuring deformations in cultural heritage and archaeological areas affected by geo-hazards (Polcari *et al*, 2015; Fassi *et al*, 2013; Jiang *et al*, 2012). GNSS provides geo-referenced coordinates that prove very useful when combined with other techniques as well as they are suitable in documenting structural deformations (n, 2015). Electronic data collection with total stations permits rapid acquisition of large amount of field data, combined with an efficient and error-free transfer of data to a processing computer/center (Haddad, 2011).

A local geodetic network is first established within the cultural heritage site. The network consists of a reference point and additional nodes which are established at specific points of interest in the landscape, such as points on peaks or ridges that may indicate/warn of a potential hazard. 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 (Themistocleous *et al*, 2017a; Themistocleous *et al*, 2017c).

There are various GNSS units that can be used to establish the geodetic network. In this case study, the Trimble Zephyr 2 GNSS antenna, Trimble R9s and Leica GS15 Smart GNSS Receivers were used for establishing a GNSS control network. The Trimble Zephyr 2 GNSS antenna offers robust low elevation tracking and sub-centimeter phase center repeatability is effective as it can withstand shock and vibration. In addition, it is capable of multipath reduction and low elevation satellite tracking. The Trimble Zephyr 2 GNSS antenna enables sub-millimeter phase centre accuracy and supports signals from GPS, GLONASS, Galileo, BeiDou, OmniSTAR, and SBAS. The Leica GS15 Smart GNSS Receivers are recommended as they adjust to any environment and deliver the most accurate results. Along with the Trimble R9s receivers, they support multi-frequency, multi-constellation GNSS (i.e. GPS, GLONASS, Galileo, BeiDou). Trimble R9s is a state-of-the-art modular receiver suitable for lengthy static positioning campaigns. Leica GS15 can also be used for Real Time Kinematic (RTK) applications as they are equipped with appropriate modems GSM/GPRS/UMTS/CDMA and UHF/VHF modem to enable corrections relay from reference stations.

D. ***Ground Sensors***

Monitoring of kinematic, hydrological and climatic parameters plays a significant role in creating relevant 3D models and simulations of the cultural heritage site and surrounding area. Geotechnical and environmental factors enable the correlation of geo-hazard events against their triggering mechanisms and assist in identifying the causal factors that necessitate geo-hazard monitoring and simulation studies (Themistocleous, 2018). However, geotechnical instruments for surface and subsurface movement monitoring, such as inclinometers and extensometers, are incapable of large-scale and long-distance monitoring (Zhu *et al*, 2017). Most ground 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 provides a continuous monitoring of the displacements from few millimeters per day up to 1 or more meters per day over unstable areas. GB-InSAR technology allows the assessment of ground deformations of fast landslides, thanks to the possibility of realizing higher frequency measurements (Corsini *et al*, 2006; Noferini *et al*, 2008). A GB-InSAR can also be placed in front of steep slopes, which are in most cases not visible from space-borne platforms. A GB-InSAR system consists in a computer-controlled microwave transceiver, characterized by a transmitting and receiving antenna that through moving along a mechanical linear rail, can synthesize a linear aperture along the azimuth direction. The transmitting antenna produces step-by-step continuous waves at discrete frequency values, sweeping a specific bandwidth generally in Ku band. Fiber Bragg grating (FBG) sensors can be used to measure changes in temperatures, displacements, loads, earth pressures, pore water pressures and soil moistures with high accuracy (Zhu *et al*, 2017). FBG sensors have been recently developed; therefore, they should be used with other geotechnical instrumentation to ensure accurate and real-time measurements. 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 logged 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. In contrast, accelerometers are used to measure acceleration force.

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. However, excessive drift in the raw measurements render accelerometers incapable to provide alone reliable data. Hence, acceleration data are fused with other sensors to augment displacement information (Smyth & Wu, 2007). On the other hand, crack meters form a mechanical but reliable and inexpensive means for early detection of deforming mass movements and measure the displacement between two points on the surface that are exhibiting signs of separation. A variety of other crack meters including vibrating-wire sensors, dial gages, and mechanics feeler gages may be used to measure movement of cracks (Federal Energy Regulatory Commission, 2018). 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), though they may be installed in other orientations. 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 .Inclinometers are geotechnical instruments used to monitor subsurface movements and deformations for long-term, precise monitoring horizontal displacements and also to monitor the rate of movement. Inclinometers consist of specially shaped casing, a probe and readout device. The inclination of the casing is measured at regular intervals and lateral movement with respect to the bottom of the casing is calculated (Federal Energy Regulatory Commission, 2018). Tiltmeter stations proved efficient in monitoring slope stability in highly active geological environment and continue to act as substantial part of mine monitoring systems. Tiltmeters consist of a base plate, sensor, and readout device. They are commonly attached to an internal or external surface of a structure and measure vertical rotation of the surface (Federal Energy Regulatory Commission, 2018).

IV. Methodology

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 (Margottini *et al*, 2015; Novellino *et al*, 2018; Margottini *et al*, 2018). 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 (Themistocleous, 2017; Themistocleous *et al*, 2017).

For the Choirokoitia cultural heritage site, the below methodology was used (Figure 2) in order to assess the risk from geo-hazards on the archaeological sites and monuments from a geospatial perspective. The research 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, material and landscape (Themistocleous *et al*, 2016). The methodology begins by monitoring the area of interest using InSAR images to detect signs of natural hazards in the UNESCO World Heritage demonstration sites using PS methods. When InSAR ground motion data indicate that a geo-hazard is evident at or near the demonstration site (in this case the Choirokoitia cultural heritage 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 resulting damage can be performed through photogrammetry using images acquired by UAVs and/or drones. Measures for calibrating these products are taken using GNSS and conventional surveying techniques. Once the resulting change or hazard has been identified using field verification, InSAR images are used again to verify and assess the extent of the damage to the cultural heritage site over time (Themistocleous *et al*, 2018). The methodology can be combined with a multi-criteria analysis of cultural heritage sites to estimate the severity of geo-hazard such as earthquakes, landslides, etc. (Silvestrou & Themistocleous, 2018).

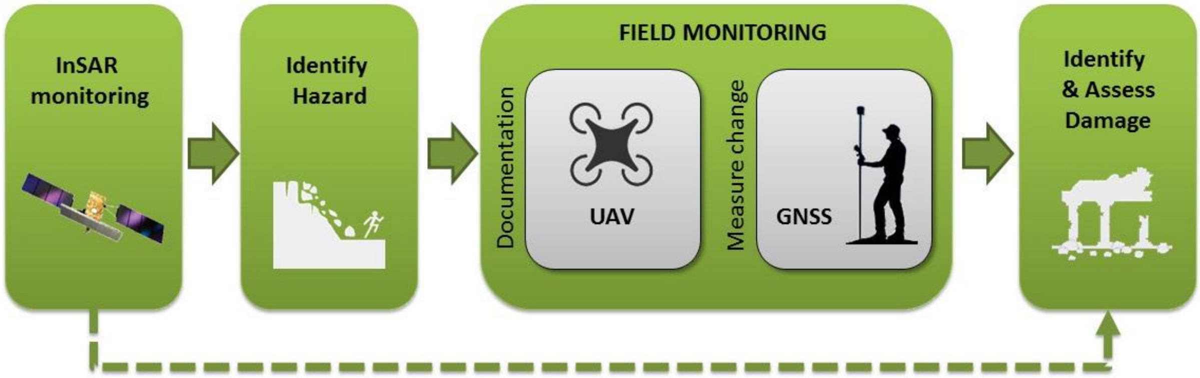

Fig 2. Methodology

To document cultural heritage sites under threat from geo-hazards, UAV images can be used to create ortho-photos, dense point clouds, 3D model and Digital Elevation Models (Themistocleous, 2017, Hu *et al*, 2019, Apollonio *et al*, 2014). 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 cloud 3D model of the demonstration site and also for comparison over temporal intervals.

In this study, two types of GNSS receivers were used for data acquisition; (a) 3 Trimble R9s equipped with Zephyr 2 Geodetic GNSS antennas, and (b) a Leica GS15 Smart GNSS receiver were used to monitor displacements via static positioning. The receivers were 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 (figure 3).

Fig 3. Panoramic photo of the Choirokoitia site and installation of the GNSS antenna

A local geodetic network was established within the cultural heritage site. Under the supervision of the Cyprus Department of Antiquities, the team was allowed to install 4 points in critical locations, following consultations from geologists and archaeologists to identify the high-risk areas within the site. For the reference stations, a point installed on solid bedrock outside the project area was selected as the reference station (CHR3) whilst three points were set up in carefully selected locations, including the top of rocks or ridge lines (figure 4)

Fig. 4 Locations of the reference station (CHR3) and three points (CHR1, CHR2 and PILR)

The data acquisition period for each station was 6 hours. Vertical motion was initially planned to be measured using an industrial grade digital level, namely, a Leica LS15 (0.15mm/$\sqrt{km}$) combined with INVAR staffs. However, due to technical difficulties (site restrictions), levelling was not eventually completed. The geodetic network was treated as a local network without directly including one of the national permanent reference stations. The main reasons behind this decision was the fact that the national network of permanent GNSS stations (CYPOS) is a Tier-3 network, i.e. it provides Single Base or Network RTK services with accuracies at the order of few centimeters. Tier-3 stations are mainly installed on top of buildings using looser monument stability specifications with respect to deformation monitoring applications. Therefore, to achieve millimeter-level results, specifically designed braced configurations were installed directly inside bedrock using high-quality resin (Hilti HIT-RE-500v3). In this way, the local network was comprised of small baselines and all benchmarks had the same degree of stability in order to avoid compromising the position solution. For georeferencing purposes, the reference (fixed) point CHR3 was independently solved using data from the CYPOS permanent station network. However, deformation analysis was not carried out using grid coordinates but within a local coordinate frame.

V. Results

In order to support field monitoring, geometric documentation of the area was performed using Real-Time Kinematic (RTK) GPS/GNSS measurements (ground control points) with images taken by UAV systems and processed using photogrammetry techniques. This data was supported and geo-referenced using the local geodetic network points. The network was measured via contemporary GPS/GNSS receivers (modular Trimble R9s and Trimble Zephyr 2 Geodetic antennas) mounted on the specifically designed braced poles fitted in solid rock (see Figure 5). The GNSS raw observables were processed using Trimble Business Center as a fixed double-differencing solution.

In this study, the documentation focused on reconstructing 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 cultural heritage site. As part of the local-scale monitoring scheme of the Choirokoitia demonstration site, the DJI Inspire 2 UAV, with a 24 MP camera, was used to acquire images that were processed using photogrammetry to produce Digital Elevation Models (DEM) and ortho-images for comparison over temporal intervals (Themistocleous, 2018). The UAV was flown at 40 meters high from the highest elevation point of the site. The speed was 6 meters per second in order to get stable images. 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.

Fig 5. GPS/GNSS receivers mounted on specifically designed metallic poles and fitted in solid rock

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. Sixty GCPs were distributed around site to correct the scale and geo-reference the model due to the morphology of the site, especially its steep incline of the hill of approximately 50 meters. The root mean square error (RMSE) of the control points were 5cm with ground resolution of 1.38cm per pixel. The images were geo-referenced using the LTM CGRS93 / Cyprus Local Transverse Mercator projection coordinate system with the Cyprus Geodetic Reference System 1993 Datum and WGS 84 Ellipsoid.

The images were then pre-processed by removing the lens distortion and then processed using the Agisoft Photoscan Professional software. The processing began with the ortho-mosaic production from these multiple images, which was used for digital terrain modelling (DTM) production from which a contour map was generated. 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 acquired on October 29, 2016; February 2, 2017; November 11, 2017 and March 7, 2018, ortho-photos and cloud 3D models were created, as seen in Figure 6 and Figure 7. The area of interest is outlined in red. All clear images with sufficient overlap were included in the processing in order to generate a dense point cloud of the Choirokoitia site.

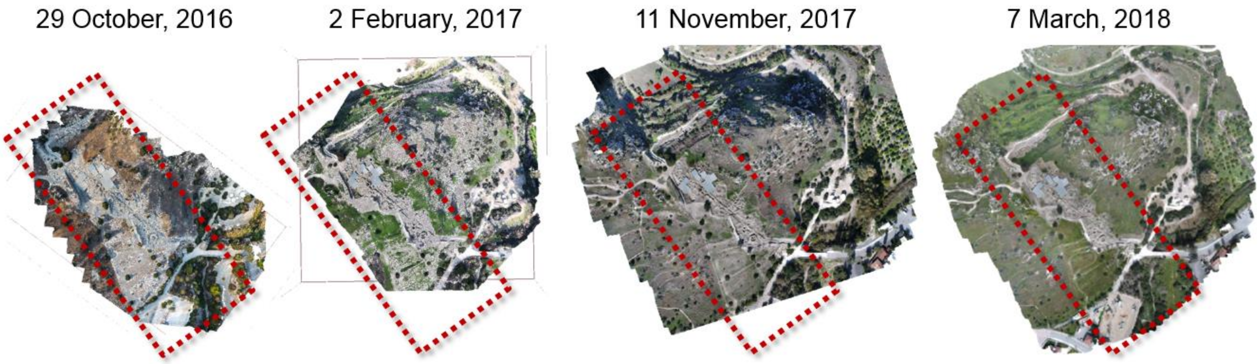

Fig 6. Ortho-photos obtained from UAV flights

Following the generation of point clouds from the UAV images using a distribution of GCP throughout the site, the model had sub-centimeter accuracy, which was critical in order to compare the 3D model with the GNSS measurements. Figure 7 depicts the final 3D model of the Choirokoitia site that was generated from the UAV images.

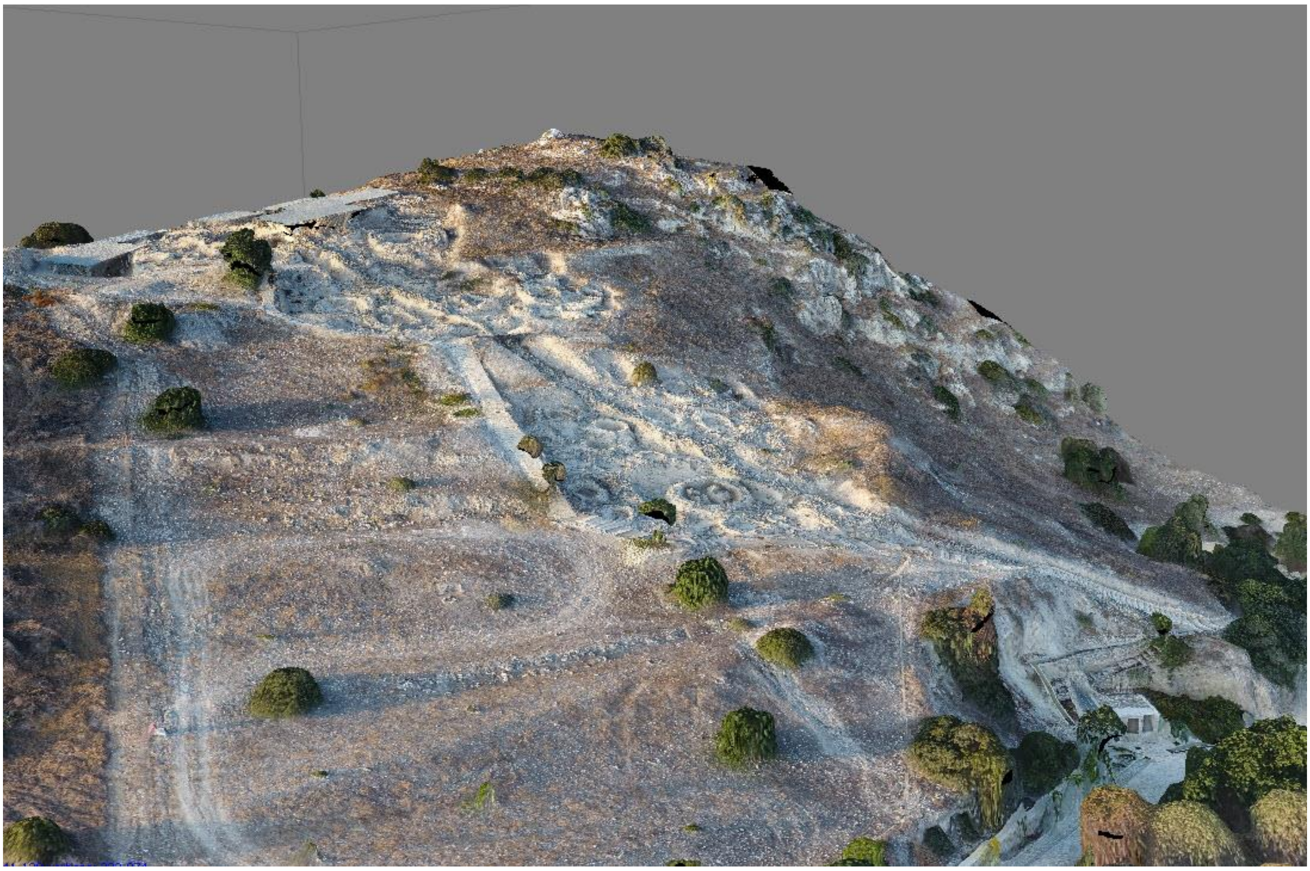

Fig .7 3D model of Choirokoitia site

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 (figure 8, lest) while the images acquired in February 2017 and March 2018 (see Fig. 8, right) 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. The voids created from the removal of the vegetation points were calculated by interpolating the points around the voids.

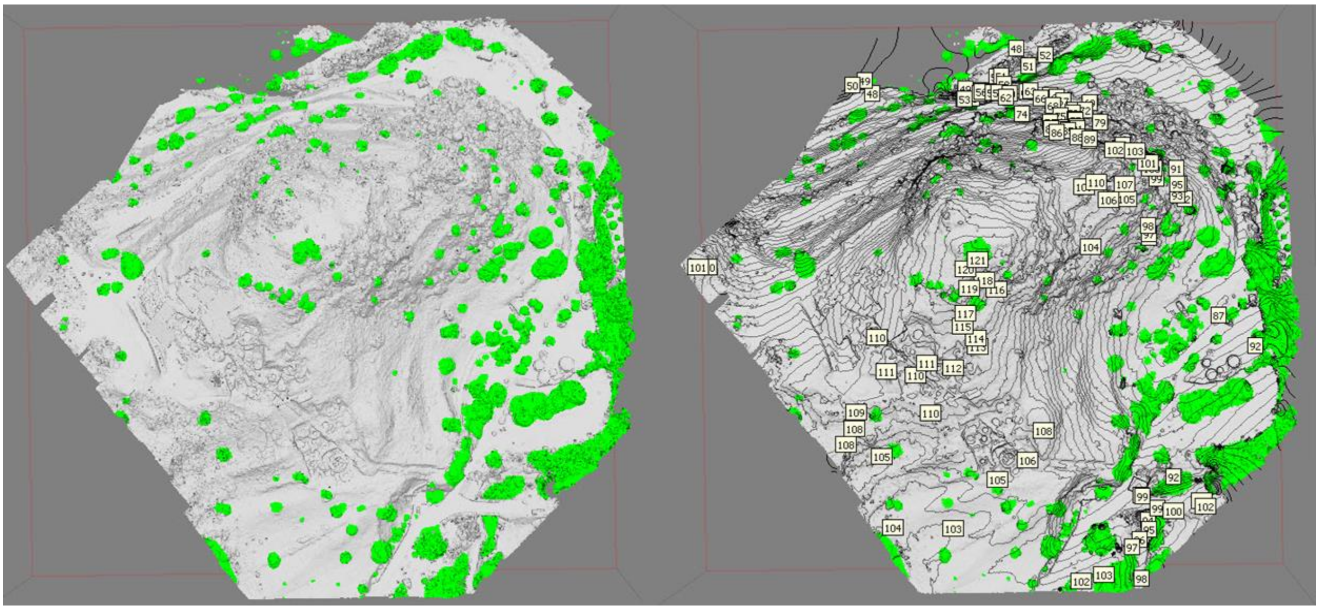

Fig. 8 Vegetation Subtraction and contour generation

Consequently, Digital Elevation Models (DEMs) and Elevation Contour Maps were generated using the point cloud models. The DEMs generated from the images acquired in February 2017, November 2017 and March 2018 were used to examine the changes and deformations in the Choirokoitia cultural heritage site over time. The DEM resolution generated by the SfM was 5.54cm per pixel. The results were compared with the GNSS measurements and the InSAR images. During the 13-month monitoring period, all the measurements recorded showed a slight shift at the top peak of the hill, at the point of PILR in the range of 2cm.

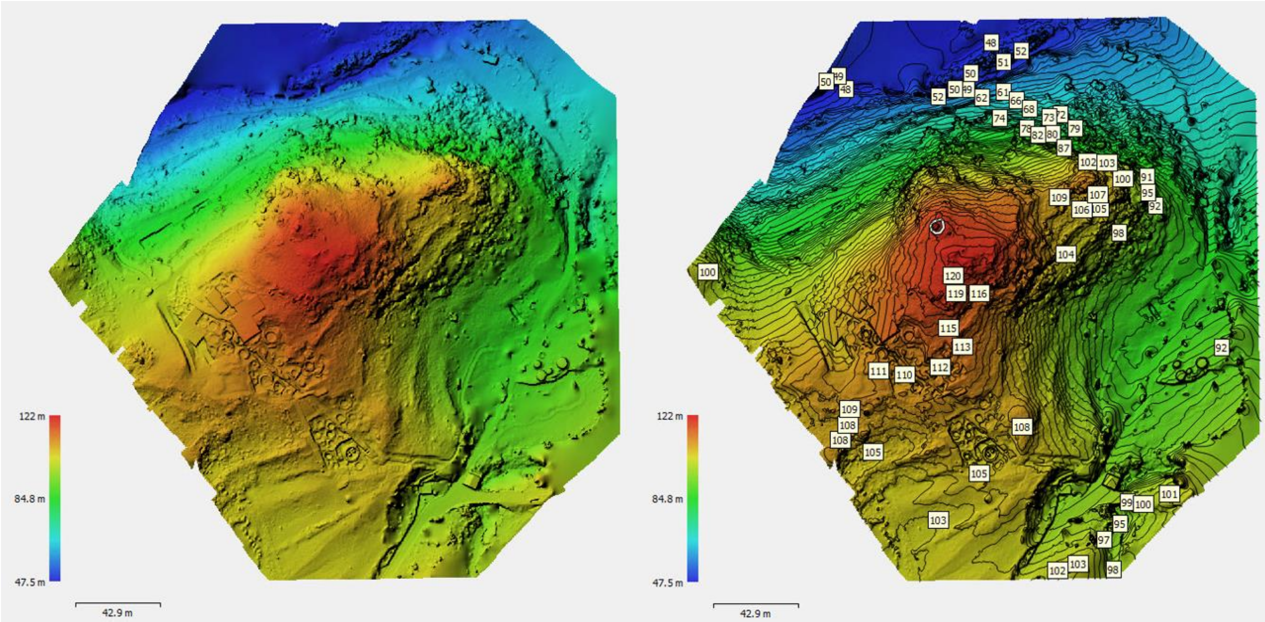

Fig 9. DEM and contour lines generated from the UAV images

Deformation monitoring was also carried out by means of two GPS/GNSS campaigns of the geodetic network in the area of interest within a 5-month period (May 19, 2017 and October 26, 2017), GNSS observations of 1 Hz were collected for a timespan of six hours for each time. The point adjustments were carried out using the Trimble Business Center software. Table 1 provides a summary of the results obtained from processing the GNSS control network during the 5-month period. 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 (CHR3) and are illustrated in Table 1.

Table 1. 3D displacements computed for the GNSS control network

GPS/GNSS Station	DE Meters	DN Meters	DU Meters
CHR1	+0.0023	-0.0025	-0.0027
CHR2	+0.0022	-0.0001	+0.0017
CHR3	+0.0000	+0.0000	+0.0000
PILR	+0.0024	+0.0001	**-0.0203**

The results of the GPS/GNSS campaigns indicate a change of 2 cm in the vertical component (Up) within the 5-month period. Furthermore, a PSI (Persistent Scatterer Interferometry) analysis was conducted on the Choirokoitia broader area to determine potential displacements by using 26 Cosmos Skymed SAR images, provided by the Italian Space Agency, from the years 2011-2017. During this time span, the points exhibit an average velocity of 3.3 cm per year. 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 present of water which also affects radar reflectivity (dielectric constant). If required, precipitation and temperature data from the area can help with determining the cause of the movement. The lower threshold for coherence was set to 0.75 to allow a sufficient number of identified targets. However, it is suggested to filter out points with a coherence lower than 0.801 using a GIS software for the most reliable results. As expected, since the AOI is primarily a rural area, the number of PS targets identified may be insufficient. The technique of SBAS is more suitable for applications on rural areas, given that the movement follows a linear trend. The results, however, provide a good indication for the overall ground stability of the area.

During the study period, PSI indicated a displacement identical to the GNSS measurements point shown for the PILR station, which is indicated by the red dot of the Choirokoitia site (figure 10). The results of the PSI analysis reveal a similar displacement pattern at the broader area occupied by the GNSS control network. 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.

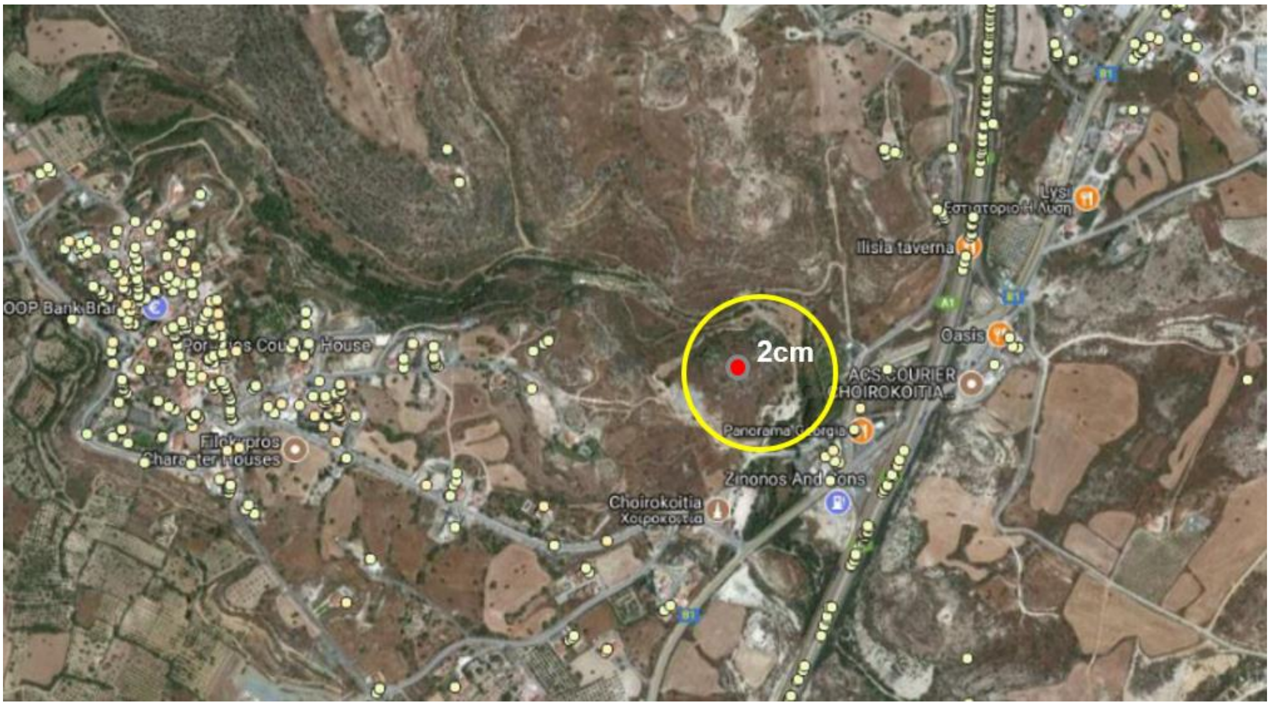

Fig 10. PSI analysis of the test site.

VI. Further research

The above methodology for monitoring geo-hazards will be further developed in the 'Cyprus Continuously Operating Natural Hazard Monitoring and Prevention System' (CyCLOPS) project, which will utilize novel space technologies along with state-of-the-art processing techniques to monitor the effects of geohazards, such as earthquakes and landslides, and assess their impact on the built environment, cultural heritage landmarks and geodetic infrastructure (Danezis *et al*, 2019). The novel multi-sensor, co-located configurations, which include permanent GNSS reference stations, weather stations, tiltmeters along specifically designed Corner Reflectors (CRs) will be established throughout Cyprus. CRs are installed in-situ provide a strong response in the SAR images resulting in good interferometric phases to derive the deformation estimates. The high reflectance of CRs allows their position within a SAR image to be determined at a very high degree of precision. Past research has found that the use of TerraSAR-X InSAR data and Corner Reflectors achieves centimetre level accuracy (Balss *et al*, 2014). Consequently, it is expected that CyCLOPS will be able to provide an estimation of ground deformation at the centimetre to millimetre level accuracy (Danezis *et al*, 2019).

VII. 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, the local-scale monitoring methodology can be used to monitor the movement of geo-hazards at affected cultural heritage sites, in order to identify the best mitigation and conservation strategy to protect these sites.

Further study of geohazards will be examined in the CyCLOPS project in order to establish of a novel strategic research infrastructure unit for monitoring solid earth processes and geohazards in Cyprus and the broader EMMENA region. 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. These activities will be further studied and developed under the auspices of the EXCELSIOR project, which is developing a Center of Excellence that will focus on Earth observation monitoring in Cyprus and the EMMENA region.

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