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<td>PROTHEGO partners external review</td>
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<td>05/03/2018</td>
<td>LEONI, G</td>
<td>PROTHEGO partners external review</td>
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<td>MARGOTTINI, C</td>
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Executive summary

The aim of the PROTHEGO project (www.prothego.eu) is to develop and validate an innovative multi-scale methodology for the detection and monitoring of European Cultural Heritages exposed to natural hazards, namely monuments and sites potentially unstable due to landslides, sinkholes, ground settlement, active tectonics as well as monument deformation, all of which could be affected by climate change and human interaction. PROTHEGO provides a new, low-cost methodological approach for the safe management of cultural heritage monuments and sites located in Europe, by integrating novel space technology based on radar interferometry (InSAR), long-term low-impact monitoring systems and indirect analysis of environmental contexts to retrieve information on ground stability and motion in the UNESCO's World Heritage List monuments and sites of Europe (Margottini et al, 2016; Themistocleous et al, 2016a). This report will examine the local scale high tech monitoring techniques that can be used on cultural heritage sites that are affected by geo-hazards, in order to identify how low impact monitoring techniques can be used for heritage conservation.

PROTHEGO's locale scale monitoring in Choirokoitia provides an example of how to detect and analyze deformation phenomena for monitoring and predicting geo-hazards using InSAR ground motion data and field survey techniques to measure and document the extent of damage of the natural hazard on the cultural heritage site. The InSAR data, GNSS, total station and level are used to measure the micro-movements, while the laser scanner, UAV and photogrammetry are used for documentation purposes and 3D modeling comparison. Local-scale monitoring data is the base for the development of geological and geotechnical modelling of the investigated sites, which will provide evolution models for the deformation processes affecting the heritage sites in order to recognize the best mitigation strategies and to evaluate the effectiveness of these actions for cultural heritage protection.
# Table of contents

1 Introduction ................................................................................................................................... 1

2 Locale scale monitoring ................................................................................................................. 2
   2.1 Methodology .......................................................................................................................... 3
   2.2 Satellite Imagery .................................................................................................................... 4
      2.2.1 Use of Corner Reflectors for Geo-location Accuracy ..................................................... 5
   2.3 Unmanned Aerial Vehicles (UAVs) ........................................................................................ 6
   2.4 Surveying techniques ............................................................................................................ 8
   2.5 Geodetic techniques .............................................................................................................. 8
   2.6 Ground Sensors ................................................................................................................... 10
      2.6.1 GB-InSAR ...................................................................................................................... 10
      2.6.2 Fiber Bragg grating (FBG) ............................................................................................ 10
      2.6.3 Capacitive sensors ....................................................................................................... 11
      2.6.4 Piezometer .................................................................................................................. 11
      2.6.5 Accelerometer ............................................................................................................. 11
      2.6.6 Crack Meters ............................................................................................................... 12
      2.6.7 In-place Inclinometer .................................................................................................. 12
      2.6.8 Tiltmeters .................................................................................................................... 13
      2.6.9 Extensometers ............................................................................................................. 13

3 Documentation ............................................................................................................................ 14

4 Conclusions .................................................................................................................................. 15

References ........................................................................................................................................... 16
1 Introduction

Tangible cultural heritage includes various categories of monuments and sites, from cultural landscapes and sacred sites to archaeological complexes, individual architectural or artistic monuments and historic urban centres. Such places are continuously impacted and weathered by several environmental and anthropogenic factors, including climate change, precipitation, natural hazards, wars, etc (Agapiou et al, 2016; Agapiou et al 2015; Margottini et al, 2016; Themistocleous et al, 2016a). However, there is limited data available regarding the effects of geo-hazards on cultural heritage sites (Themistocleous et al, 2016b).

The aim of the PROTHEGO project (www.prothego.eu) is to develop and validate an innovative multi-scale methodology for the detection and monitoring of European Cultural Heritages exposed to natural hazards, namely monuments and sites potentially unstable due to landslides, sinkholes, ground settlement, active tectonics as well as monument deformation, all of which could be affected by climate change and human interaction. PROTHEGO provides a new, low-cost methodological approach for the safe management of cultural heritage monuments and sites located in Europe, by integrating novel space technology based on radar interferometry (InSAR), long-term low-impact monitoring systems and indirect analysis of environmental contexts to retrieve information on ground stability and motion in the UNESCO’s World Heritage List monuments and sites of Europe (Margottini et al, 2016; Themistocleous et al, 2016a). This report will examine the local scale high tech monitoring techniques that can be used on cultural heritage sites that are affected by geo-hazards, in order to identify how low impact monitoring techniques can be used for heritage conservation.

In the past decades, it was widely recognized that cultural heritage can be highly vulnerable to geological disasters induced by earthquakes, volcanoes, floods and catastrophic landslides. As well, cultural heritage is vulnerable to other non-catastrophic slow-onset geo-hazards that can slowly affect the integrity and accessibility of the heritage, such as slow-moving landslides, sinkholes, ground settlement and active tectonics. Even if these phenomena can be responsible for large damages, they are largely neglected in the literature (Gutiérrez & Cooper, 2002; Rohn et al, 2005; Canuti et al, 2009). The long-term vulnerability of cultural heritage is commonly focused on the heritage itself (i.e., degradation and corrosion of building materials) in response to environmental risks (Brimblecombe, 2000; Fort et al, 2006), without fully considering or understanding the entire
geological and geotechnical context. Currently, assessing geo-hazards in cultural heritage sites takes place after the geo-hazard has occurred. However, the high costs of maintenance of cultural heritage sites directly enforce the prioritisation of the monitoring and conservation policies to ensure sustainable conservation. Monitoring the deformation of structures as well as their surroundings facilitates the early recognition of potential risks and enables effective conservation planning (Tang et al 2016).

On-site observation has been the most common way of monitoring cultural heritage sites and monuments in Europe. However, this procedure, that includes field surveying, ground-based data collection and periodical observations, can be time consuming and expensive, especially over large or remote areas is extremely difficult, expensive and time consuming. (Themistocleous et al, 2016a). Traditionally, deformation monitoring in cultural heritage sites is carried out by installing electrical sensors in selected structures with automatic systems for data acquisition and recording or by using portable instruments with manual reading of data taken at fixed time intervals (Zhou et al, 2015; Garziera et al, 2007; Glisic & Inaudi, 2008). However, such methods can only acquire data of the monitored structure within the cultural heritage sites, not the entire area of the site and its surrounding landscape (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 availability of the heritage.

2 Locale scale monitoring

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 using precise ground measurements. **Once vulnerable sites are identified by InSAR satellite imagery, local-scale monitoring and advanced modeling can be used to monitor the cultural heritage sites over time.** The locale scale monitoring methodology includes in-situ observation and remote sensing techniques, such as PS techniques, that are used to validate the impact of natural hazards. Topographic surveying using differential GNSS, Unmanned Aerial Vehical (UAV) images, photogrammetry and InSAR data are used to map slow ground movements, which are then compared and validated with ground based
geotechnical monitoring in order to evaluate cultural heritage sites deformation trend and to understand its behaviour over time. As a result, areas exposed to potential risks and their evolution in time can be identified and crucial information can be provided to decision makers in order to protect cultural and heritage sites from natural hazards.

**Locale scale monitoring provides the opportunity to detect and analyze deformation phenomena for monitoring and predicting geo-hazards using field survey techniques to measure and document the extent of damage of the natural hazard on the cultural heritage site.**

The geodetic techniques can be used in combination with UAVs for documentation purposes and 3D modeling comparison. The aerial imagery obtained from the UAVs can be imported into *Structure in Motion* software to create rapid and automated generation of a point cloud model and 3D mesh model in order to document and monitor the extent of geo-hazards at the cultural heritage site. The ground based geotechnical monitoring can then be compared and validated with InSAR data to evaluate cultural heritage sites deformation trends.

### 2.1 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). 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.

For the PROTHEGO study, a methodology was developed for local-scale monitoring in order to assess the risk from natural 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 contexts to investigate changes and decay of structure, material and landscape (Themistocleous et al, 2016a).

The methodology for the locale scale monitoring begins with using InSAR images to identify natural hazards in the UNESCO World Heritage demonstration sites. When the InSAR ground motion data indicate that a natural hazard took place at or near the demonstration site, field monitoring and verification is necessary to document and measure the extent of the change caused by the natural
hazard, if any. Documentation of the damage can be performed either close range, using laser scanning or photogrammetry, or by low altitude sensors, using UAVs and drones. Measurements for calibration of these products are taken using GNSS and total station. After the change is identified using field verification, InSAR images are again used to verify and assess the extent of the damage to the cultural heritage site. The methodology is presented in figure 1.

![Methodology for local scale monitoring](image)

**Figure 1. Methodology for local scale monitoring**

For this report, the local scale monitoring is focused primarily on field monitoring as a method of measuring change and documenting the geo-hazard.

### 2.2 Satellite Imagery

By examining vast regions of interest from 800 km above the Earth’s surface, 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 estimating, with up to millimetre precision, subtle and non-catastrophic, long-term and seasonal land processes that 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 cause and extent of the observed motions.

Satellite Synthetic Aperture Radar (SAR) images acquired by active radar sensors are processed with multi-interferogram methods – such as the Persistent Scatterers (PS) and Small Baseline Subset (SBAS) techniques, and used to extract information on ground displacement 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; Cigna et al, 2012; Cigna et al, 2014). Differential Interferometric SAR (InSAR) methods combine the radar returns from two or more radar scenes over the same area to detect changes occurred between acquisitions with precision up to the millimeter level, allowing for the monitoring of even subtle ground movements – down to a few millimetres – across wide areas (Chen et al, 2015; Tapete et al, 2013; 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/historical landscape, site detection and feature extraction (buried or emerging archaeological remains), change detection and structural monitoring (Cigna et al, 2012; Lasaponara & Masini, 2013; Tapete et al, 2012; Tapete et al, 2016; Cigna et al, 2013).

The Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) technique is used in remote sensing as a method for monitoring ground displacements induced by geo-hazards and anthropogenic phenomena. The 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). 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.

### 2.2.1 Use of Corner Reflectors for Geo-location Accuracy

If long-term surface coherence changes due to vegetation and moisture (temporal de-correlation) are significant, it will be impossible to obtain a cumulative deformation map through D-InSAR. Therefore, PS Interferometry can be performed by relying on fixed targets, often called coherent scatterers or point scatterers (PS). Common point scatterers could be buildings, outcrops, vehicles, 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. 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, levelling, inclinometers) and used as initial input for any geotechnical modelling.
2.3 Unmanned Aerial Vehicles (UAVs)

UAVs have become a common tool in cultural heritage and archaeological research as they provide higher resolution images compared with satellite imagery. Research indicates that unmanned aerial vehicles (UAVs) can be used for low-altitude imaging and remote sensing of geospatial information (Colomina & Molina, 2014; Themistocleous et al, 2014a; Themistocleous et al, 2014b Themistocleous et al, 2014c). UAVs are being used for surveying cultural heritage sites due to their affordability, reliability and ease-of-use (Themistocleous et al, 2015a; Themistocleous et al, 2015b; Themistocleous et al, 2015c; Lo Brutto et al, 2014; Burkhart et al, 2014; Colomina & Molina, 2014). UAV data provides more detailed surveys of the archaeological site (Hassani, 2015; Remondino & Rizzi, 2009; El-Hakim et al, 2004; Gruen et al, 2005; Rönnholm et al, 2007; Guidi et al, 2009a), 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).

Remote sensing technologies on a UAV platform are extremely useful for the detection and monitoring of cultural heritage features (Themistocleous et al, 2014a; Themistocleous et al, 2014b; Themistocleous et al, 2014c; Agapiou et al, 2013). UAVs can be a efficient, non-evasive and low cost resource to document cultural heritage sites (Themistocleous et al, 2014a; Themistocleous et al, 2014b; Themistocleous et al, 2014c; Agapiou et al, 2013) and can be fitted with sensors which are able to produce an unprecedented volume of high-resolution, geo-tagged image-sets of cultural heritage sites from above (Themistocleous et al, 2014a; Themistocleous et al, 2014b; Kostrzewa et al, 2003; Ruffino & Moccia, 2015; Scholtz et al, 2011).
To document cultural heritage site under threat from geo-hazards, UAV images can be used to create ortho-photos, dense clouds, 3D model and Digital Elevation Models. The UAVs should be equipped with a 20mp camera to acquire images over the site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-image and point cloud 3d model of the demonstration site and also for comparison over temporal intervals.

In order to utilize the UAV images, it is necessary to position and measure Ground Control Points over the entire area prior to the flight, in order to make the necessary corrections during the post-processing of the images. These corrections are required to ensure the correct scale of the model, that is necessary to accurately print the model in scale. The GCPs points must be recorded with a
double frequency GNSS system with estimated accuracy of less than 2cm. The UAV will then be flown over the designated site at a height of 60 meters at the highest point. Flight planning software can be 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. The UAV camera should take images with a 80% overlay within each image. In this way, single images can automatically be built into a large detailed map, to correct distortions and create a 3-D model.

2.4 Surveying techniques
For the local-scale monitoring, surveying techniques are used to determine the absolute positions and positional changes of any point on the surface and geotechnical techniques to measure deformation over a relatively short measurement base. Surveying techniques, such as total station, leveling, and Global Navigation Satellite Systems (GNSS), are used to measure the positional changes of any point on the surface at millimeter level accuracy. They have also been successfully used for measuring deformations in archaeological areas affected by hazards (Polcari et al, 2015; Fassi et al, 2013; Jiang et al, 2012). GNSS provides location coordinates in global geographical system, highly useful in combination with other techniques, being appropriate in documenting mass targets and structural deformation (Hassani, 2015). Electronic data collection with total station instruments permits the quick acquisition of large amounts of field data, together with the efficient and error-free transfer of the data to a computer (Haddad, 2011).

2.5 Geodetic techniques
A local geodetic network is first established within the cultural heritage site. The network consists of a reference point and additional nodes, established at specific points of interest (i.e. points on peaks or ridges that may indicate/warn of a potential hazard). 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.

There are various GNSS units that can be used to establish the geodetic network. The Trimble Zephyr 2 GNSS and Leica GS15 Smart GNSS Receivers are recommended for establishing a GNSS control network. The Trimble Zephyr 2 GNSS offers robust low elevation tracking and sub-millimeter 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 support sub-millimeter phase centre accuracy and support 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 delivers the most accurate results. They use multi-frequency, 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.

Horizontal displacements can be measured using an industrial-grade total station, such as the Topcon MS05AXII, which has a 0.5” angular accuracy and 0.5mm range accuracy, combined with specifically designed prisms and reflective targets to achieve maximum accuracy in validating potential displacements. Vertical motion can be measured using a high-precision digital level, such as the Leica DNA03. The leveling campaign will be carried out using Invar Barcode Staffs, achieving a vertical accuracy at the order of 0.3mm/km.
2.6 Ground Sensors

Monitoring of kinematic, hydrological, and climatic parameters plays a significant role in creating 3D models and simulations. Geotechnical and environmental factors enable the correlation of geo-hazard events with their triggering mechanisms and assist in identifying the causal parameters for geo-hazard monitoring and simulation. 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.

2.6.1 GB-InSAR

GB-InSAR is a ground-based system that works with the same principles as space-borne sensors for monitoring ground deformation phenomena. GB-InSAR allows a continuous monitoring of the 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, thanks to the possibility of realizing higher frequency measurements (Corsini et al., 2006; Noferini et al., 2008). In addition, the spatial coverage of satellite data is limited by the SAR imaging geometry caused by layover, foreshortening and shadowing effects (Ferretti et al., 2001). 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, by moving along a mechanical linear rail, is able to 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.

2.6.2 Fiber Bragg grating (FBG)

According to Zhu et al (2017), the fiber optic sensing technology of fiber Bragg grating (FBG) sensors can be used to measure variations of temperatures, displacements, loads, earth pressures, pore water pressures and soil moistures with high accuracy. 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.
2.6.3 Capacitive sensors

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.

2.6.4 Piezometer

A piezometer is designed to measure pore-water pressure. Piezometers in durable casings can be buried or pushed into the ground to measure the groundwater pressure at the point of installation. Water levels in the piezometer can either be logged manually (low temporal resolution) or automatically (high temporal resolution) and can be used to calculate pore-water pressures within the screened interval of the piezometer tip.

![Piezometer Diagram](Image)

*Figure 6: Casagrande Piezometer and Pneumatic Piezometer*

2.6.5 Accelerometer

An accelerometer is used to measure acceleration force, such as tilt. Typical accelerometers are made up of multiple axes, two to determine most two-dimensional movement with the option of a third for 3D positioning. The ADXL335 accelerometer is a low cost instrument which is highly sensitive to vibration in any of the three physical axes. The ADXL335 provides analogue voltage equivalent to imposed acceleration. It has three outputs, one each for of X-, Y- and Z-axes. The three analogue outputs are wired to Arduino Uno ADC pins. Any acceleration caused due to movement in any of the axes is detected by the accelerometer and hence by Arduino ADC.
2.6.6 Crack Meters

Crack meters are a reliable and inexpensive means for early detection of deforming mass movements. They 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.

2.6.7 In-place Inclinometer

Inclinometers are geotechnical instruments used to monitor subsurface movements and deformations for long-term, precise monitoring horizontal displacements along various points on a borehole and also to monitor the rate of movement. 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.
2.6.8 Tiltmeters

Tiltmeter stations proved efficient in monitoring slope stability in highly active geological environment and continue to act as substantial part of mine monitoring system. Tiltmeters consist of a base plate, sensor, and readout device. They are commonly attached to a surface (internal or external) of a structure and measure vertical rotation of the surface.

2.6.9 Extensometers

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.
3 Documentation

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

UAVs provide an affordable, reliable and straightforward method of capturing cultural heritage sites, thereby providing a more efficient and sustainable approach to documentation of cultural heritage sites. Recent developments in photogrammetry technology provide a simple and cost-effective method of generating relatively accurate 3D models from 2D images (Ioannides et al, 2013; Themistocleous et al, 2015a; Themistocleous et al, 2015b; Themistocleous et al, 2014a; Themistocleous et al, 2015c). Under the framework of the PROTHEGO project, hundreds of images of the Choirokoitia site were taken using a UAV with an attached high resolution camera. As part of the locale-scale monitoring of the Choirokoitia demonstration site in the PROTHEGO project, a UAV with an attached 20MP camera was used to acquire images over the site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-image of the demonstration site and also for comparison over temporal intervals. 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.

Laser scanners have become increasingly efficient in terms of point acquisition speed, portability, user friendly and cost (Fassi et al, 2013). Laser scan technology allows user to produces a high-precision digital reference data that records condition, provides a virtual model for replication, and makes possible easy mass distribution of digital data (Vilceanu et al, 2015; Hassani, 2015) of the cultural heritage site. Site documentation can be conducted using a laser scanner to monitor the site so that comparison over temporal intervals will be performed. The laser scanner cloud point can be used for further 3D modelling of the area and to generate a Digital Surface Model (DSM) of the site.
PROTHEGO’s locale scale monitoring in Choirokoitia provides an example of how to detect and analyze deformation phenomena for monitoring and predicting geo-hazards using InSAR ground motion data and field survey techniques to measure and document the extent of damage of the natural hazard on the cultural heritage site. The InSAR data, GNSS, total station and level are used to measure the micro-movements, while the laser scanner, UAV and photogrammetry are used for documentation purposes and 3D modeling comparison. Local-scale monitoring data is the base for the development of geological and geotechnical modelling of the investigated sites, which will provide evolution models for the deformation processes affecting the heritage sites in order to recognize the best mitigation strategies and to evaluate the effectiveness of these actions for cultural heritage protection.
References


