Integrated use of UAV photogrammetry and Terrestrial Laser Scanning to support archaeological analysis: the Acropolis of Selinunte case (Sicily)

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Integrated use of UAV photogrammetry and Terrestrial Laser Scanning to support archaeological analysis: the Acropolis of Selinunte case (Sicily, Italy)

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Abstract

Southwestern Sicily is an area of infrequent seismic activity, however some studies carried out in the archaeological Selinunte site suggest that, between the fourth century B.C. and the early Middle Ages, probably at least two earthquakes struck this area with energy enough to damaging and causing collapse and kinematics much of the architecture of Selinunte. Taking into account that, in 2008 a non-invasive archaeological prospection and traditional data gathering methods along the Acropolis north fortifications was carried out. Following this first studies, after about 10 years, a new geophysical campaign was carried out. This second campaign benefited from the application of modern technologies for the acquisition and processing of the point cloud data on the northern part of the Acropolis, like Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle Photogrammetry (UAVP). In this paper we present the application of these techniques and a strategy for their integration for the 3D modeling of buildings and cultural heritages. We show how the integration of data acquired independently by these two techniques is an added value able to overcome the intrinsic limits of the individual techniques. The application to the Selinunte's Acropolis allowed to highlight and measure with high accuracy fractures, dislocation, inclinations of walls, depressions of some areas and other interesting observations which may be important starting points for future investigations.

Keywords: Terrestrial Laser Scanning, Unmanned Aerial Vehicle Photogrammetry, Archaeological survey, Selinunte Archaeological Park, Digital Elevation Model, 3D reconstruction.

1. Introduction

In the last years, surveys and monitoring supported by availability of three-dimensional (3D) coordinate data, are increasingly used in the conservation and management of cultural heritage sites (Aragóna, Munar, Rodríguez, & Yamafunec, 2018; Discamps et al., 2016; Erenoglu, Akcay, & Erenoglu, 2017; O'Driscoll, 2018; Themistocleous, 2017). In particular, the data obtained from the modern powerful technological tools allow to carry out specific analyses aimed to supporting preventive conservation, as well as the digital documentation processes, recognized as essential element for the conservation. Preventive conservation of cultural heritage sites, due to damaging by human or natural events, is recognized as the best solution in place of repair activity (Costanzo et al., 2015; Wilson, Rawlinson, Frost, & Hepher, 2018; Messaoudi, Véron, Halin, & Luca, 2018; Xiao et al., 2018; Zimmer et al., 2018; Caserta et al., 2016).
The survey methods to be employed, should be chosen taking into account their efficiency in the acquisition of 3D numeric data. Most heritage sites are fairly large and so may be necessary the use of different techniques to obtain comprehensive digital models (Jo & Hong, 2019).
Proximal and distal Satellite Archaeology is a new branch for non-invasive archaeological research (Parcak, 2009). This discipline and the recent technological development around it have strongly affected the studies in Landscape Archaeology and helped researchers realize the enormous potential for better results in non-destructive archaeological studies. Usually in archaeology, it is used as a means to locate and verify presence of buried architecture as well as study their relations with their surrounding territory, to determine the exact location of ancient structures or sites, as well as pathways and connections between these sites. It is also used to determine where resources have been, and why a community may have settled in a specific area. It is not limited to what one can see with the naked-eye as there are ways to survey what lies beneath the ground. More recently though, in the wake of improvements in remote sensing technology, information is also being collected from capturing the reflections and absorptions of the other electromagnetic wavelengths: ultraviolet, the infrareds (e.g. NIR, MIR and Thermal), and microwave using both passive and active sensors such as multi-spectral scanners and radar (Costanzo et al., 2016).
The proximal remote sensing technologies are an effective and non-invasive tool to provide useful data for accurate diagnosis and current state of the art of a study area. Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle Photogrammetry (UAVP) are considered to be representative of documentation technology. Unmanned aerial vehicles or drones have become widely available for use in a broad range of disciplines. These techniques allow us to create digital models based on the recorded data that are nearly identical to the physical geometry (Angelo, Stefano, Fratocchi, & Marzola, 2018; Galantucci, Pesce, & Lavecchia, 2015; Herráez et al., 2016).
In this work, the integration of TLS and UAVP data is proposed to produce the 3D digital documentation of the Selinunte's Acropolis. The aims of this multidisciplinary research was the detailed analysis of the most important structures and the landscape, to assess kinematics behavior of the masonry segments and their defects (cracks, the disintegration of the original mortar, replacement of ashlars, etc). After checking the accuracy of the acquired data, the point clouds of the Acropolis obtained from the two techniques were integrated to produce detailed Cartographic Maps (CM) and a complete 3D Model (3DM). In Section 2 we introduce the heritage site (the Selinunte Archaeological Park) and the study area (Selinunte Acropolis) (§2.1) and describe the survey methods and their execution (§2.2). In section 3, we discuss the main results carried out by UAVP (§3.1) and TLS (§3.2), then we present the integrated digital model of the area (§3.3). Finally, in section 4 main results are summarized and some concluding remarks are outlined.

2. Materials and Methods

2.1 Heritage site and Study Area

Southwestern Sicily is an area of infrequent seismic activity. Only an earthquake occurred in the Belice valley on 13 January 1968 is reported in the historic earthquake catalogues (e.g. Rovida et al., 2020). This event, characterized by moderate-high energy (M=6.5) had significant epicentral and local macroseismic intensities (Io=X and I=VII-VIII of the MCS scale).
In particular, the Archaeological Park of Selinunte (Fig.1), the largest archaeological area in Europe, covers an area of 270 hectares, resting on rock basement attributable to the Marsala Calcarenites (a sort of limestone) (Lower Pleistocene), widely studied by Ruggeri, Unti, Unti, & Moroni (1977) and Amadori, Feroci, & Versino (1992). Geologically, the Acropolis of Selinunte was built on sedimentary soils of the Pleistocene era, consisting of sands, sandy clay and clays with levels and lens of Marsala Calcarenites (Ruggeri et al., 1977).

Some studies carried out in the archaeological Selinunte site suggest that probably at least two earthquakes struck this area, between the fourth century B.C. and the early Middle Ages, with energy able to damage and collapsing the major temples lying on the eastern hill (Pannaccione Apa, Jacoli, & Guidoboni, 2010; Boschi et al., 1995; Rovida et al., 2020; Guidoboni, Muggia, Marconi, & Boschi, 2002). The site consists of the Acropolis, the eastern hill, the plateau of Contrada Manuzza, the sanctuary of Demetra Malophoros in "Contrada Gaggera" and two necropolises (Manicalunga & Galera Bagliazzo). All the material for building the temples was obtained from the Cusa's quarries. After the temples, the defensive system that surrounds the entire Acropolis is certainly the most imposing element of Selinunte's architecture. The wall, terraced with steps (560 - 540 BC) on the east side of the Acropolis hill, was built to expand and support the terrace of temples C and D. After the destruction by the Carthaginians in 409 BC.

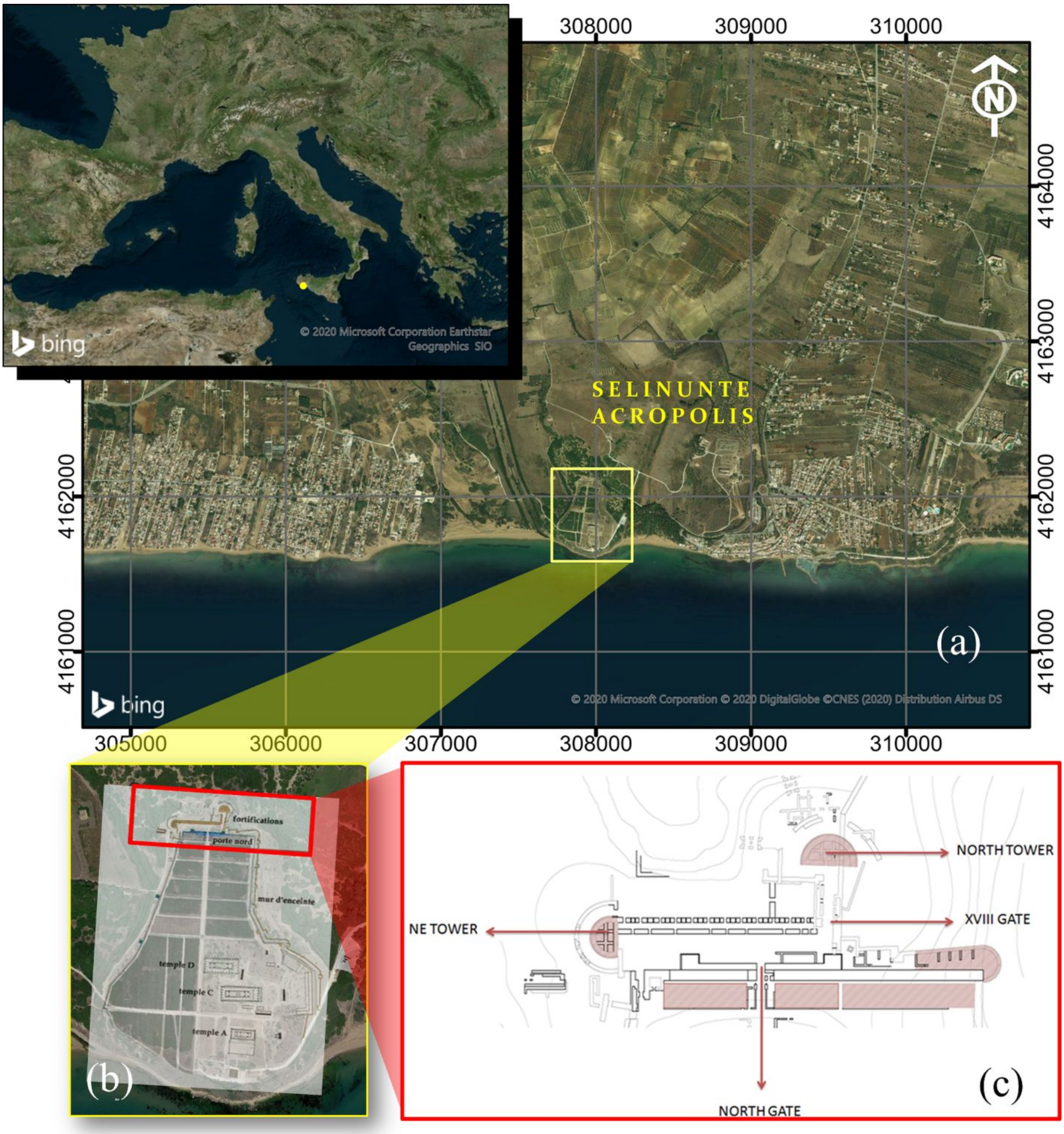

Figure 1. Location of the Archaeological Park of Selinunte in the Italian territory and of the Acropolis respect to the South-Eastern coastline of Sicily with general plan of the Acropolis (a). The test site is framed in the red rectangle: (c) detail of the North fortifications and the position of North Gate, Grand Gallery, NW and N Towers and Gate XVIII (Bassani & Besana, 2015; Tav. 04).

The walls of a city are generally the richest architectural element of information from various points of view, especially for their size and solidity that allow the preservation of important wall portions over time. Taking into account that and taking the architectural defensive walls as a study marker, Pannaccione Apa et al. (2010) carry out a specific investigation in the sector of the northern fortifications, obtaining relevant information from the remains currently in situ of the "Grand Gallery" and the two lateral towers. In particular, the choice of this study area, was motivated by the state of conservation of the portions of the raised wall, such as to allow a reading of the possible fractures and displacement of the architectural elements. Pannaccione Apa et al. (2010) recognize the damage suffered over time due to human causes and natural deterioration, as well as repairs made in ancient times and current restorations. In some cases, the recovery and conservation interventions concerned the gaps left by the deterioration of the segments, recovering the volume with the use of mortars, in some cases inconsistent and / or poorly binding.

Built with square blocks of calcarenite, the fortifications visible today belong to various chronological construction phases, in which defensive reinforcements with additional walls and new buttresses are evident, built with the assembly of parts built in different times and with different methods.

To the inner circle erected by Hermocrates after the defeat suffered by the Carthaginians in 409 BC, modifications and especially additions were made (counter walls in the East and North; doors, posts and towers along the way; northern complex and moat in the North) by his successors, always during the Hellenistic-Punic period. In addition, the circle of Hermocrates incorporates decidedly more ancient parts, as well as decidedly more recent parts: the terraced walls of the temples of temples C and D, included in the eastern section; more recent, from the Byzantine period (VI-IX century A.D.), and botched, various rows added to the walls to raise them in the points where they appeared damaged, or in any case inadequate to ensure the defense.

2.2 Survey methods

In 2008 a non-invasive archaeological prospection and traditional data gathering methods along the Acropolis north fortifications was carried out (Pannaccione Apa et al., 2010). This investigation was focused on the collection of data along the northern fortifications in order to detect and characterize, where possible, the type of damage suffered by defensive walls. In fact, the walls of a city are generally the most interesting architectural element under various points of view and their size and solidity allow the conservation over time of important wall portions (Mertens, 1989). The survey has been along the external route of the walls, starting from the west tower of the large gallery and ending along the east wall of the city's first city wall.

By examining the results obtained from the 2008 archaeological prospection, we decided to plan a specific archaeometric campaign for the acquisition and processing of the point cloud data on the northern part of the Acropolis using UAVP and TLS. We chose to use these techniques because the site is relatively wide, open, and complex, and the elements of the cultural heritage are immersed in a wild natural environment. The large extension of the entire Acropolis is mostly covered by dense Mediterranean vegetation, invading both *insulae* and part of the pathway outside the defensive walls. Therefore, documenting the shape of the entire site exclusively through terrestrial laser scanning was excluded, also given the impossibility to acquire data at positions where the scanner is inaccessible. Moreover, the acquired data has a low point density owing to the restricted field of view, even when the scan is performed for a long duration and from a high position. The superior mobility and accessibility of UAVP can be actively utilized to overcome these disadvantages. When TLS and UAVP photogrammetry can be appropriately integrated, multidirectional numerical information together with the arrangements of architectural heritage sites could be acquired. Accordingly, the fusion of laser scanning and photogrammetry has been widely used for the 3D modeling of buildings and cultural heritages.

UAVP has been performed in the study area with the aim of achieving the orthoimages and digital model of the whole selected site. In fact, the orthoimages created via UAVP allows for distances, angles, plane coordinates and areas, to be directly measured as the relationships between different locations are identical to those on the topographic map. Moreover, the Computer Vision algorithms as Structure from Motion (SfM) and Dense Image Matching (DIM), included in the classical photogrammetric procedures and the integration of sensors and data, have provided comprehensive tools for data processing, capable to supply the digital products on the Acropolis north fortifications, also in the impervious zones difficultly accessible. The results allowed us to extract information on the planar geometry of the walls and the elevation profile of the ground, as well as to cover any spatial gaps in mapping through the terrestrial laser scanning.

Instead, TLS survey was performed to obtain a high-resolution 3D model on the manmade elements of the area. A laser scanning based on the phase-shift measurement was used. This technique permits to measure with high-resolution the distance through the phase difference between the emitted and returning laser wave. By combining the distance with the two internal angle measurements of the rotating mirrors of the scanner, a spherical coordinate system centered on the sensor can be defined and any point on the surface of the object can be recorded using this spherical coordinate system. Generally, the scanner allows us to detect for each recorded point two kinds of information: the position, as a set of coordinates, and the reflectance, as the ratio between the phases (or energy) of laser wave. This method can quickly acquire the geometry of a large cultural heritage site, owing to its high operation speed, mobility, and accessibility. The data acquisition by terrestrial laser scanning allows us to obtain information along the vertical direction, which is much more difficult to achieve through an aerial survey.

The workflow, together with the scheme of the data processing that combines the two technologies is summarized in Figure 2. Through feature point matching, GCP inputting, point cloud creating, and texture mapping, UAVP produced a 3D model created from the aerial photographs obtained after the setup of a flight plan. At the same time, laser scanning collected a 3D point cloud through field scans, data registering, merging, filtering and then the two models were co-referenced. Afterwards, a 3D model based on the hybrid point cloud was generated, it including the topography and the shapes of the walls, by co-registering and merging of the point clouds, after changing the data to have compatible extensions. Conversely, for the analysis based on high-resolution geometry obtained by laser scanning, only the necessary scans were considered to reduce error due to the co-registration of the point clouds.

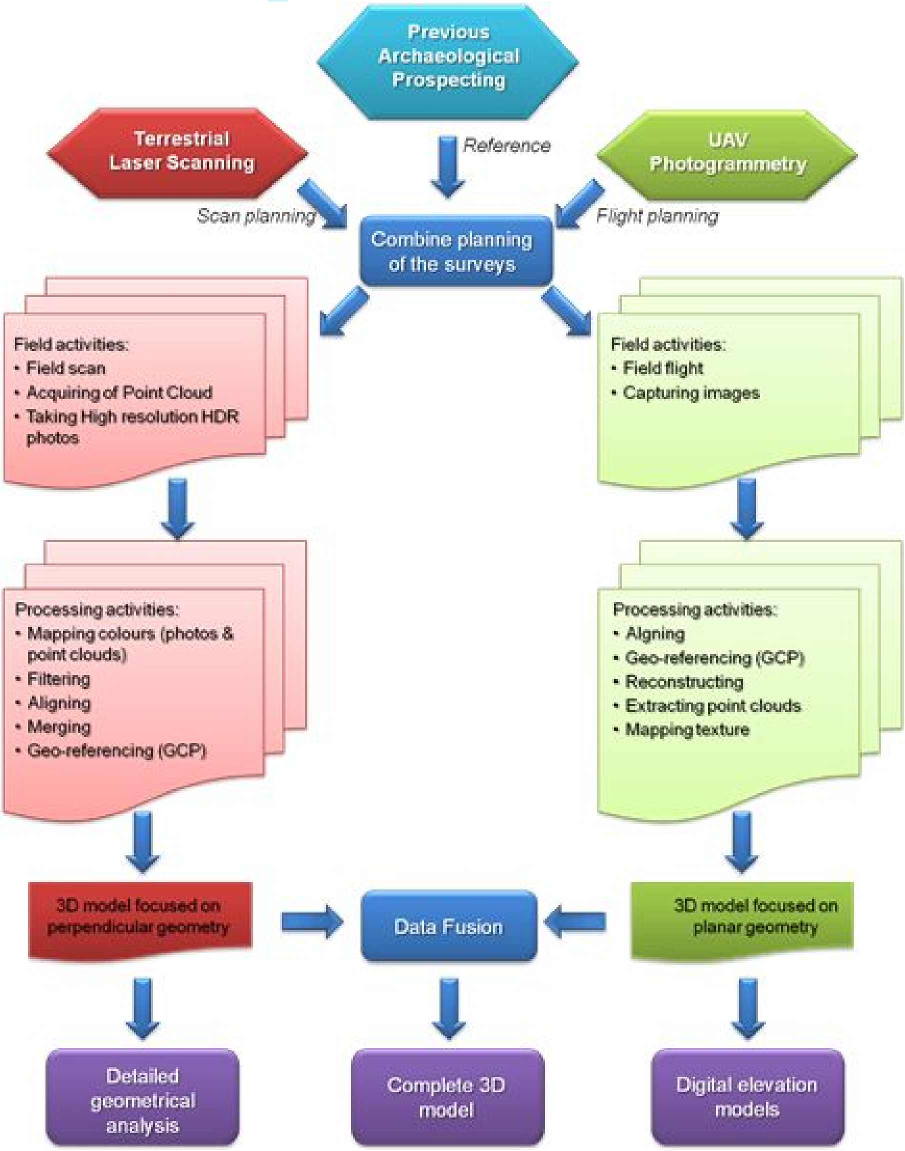

Figure 2. Workflow of the survey and processing of data using terrestrial laser scanning and UAV photogrammetry.

3. Results and Discussion

3.1. Model by UAVP

In this study, we used a DJI Phantom III Professional drone (quadcopter) equipped with a 12 Mega Pixel digital camera. Before performing drone mapping, we planed the flight paths and areas for each flight mission. For most missions, the drone was set to take aerial photographs using "autopilot mode" with a camera facing directly downwards for hilly terrain. A few surveys were conducted with the camera mounted 45° sideways to enable high-quality capture of data from steep cliff faces.
We selected 70–90% forward and sideways overlap of images. We carried out more than six flight missions, capturing a total of 3500 pictures, mapping a total area of about 0.3 km^2, focused on the North Gate and defensive walls. The acquisition of field data requires the determination of several control points on the ground, known as Ground Control Points (GCP). In this campaign 20 GCP, distributed within the defined area, were recorded. Landmarks ranged from easily-identified points in the field, such as roads or stones, along with targets and survey stakes in areas with vegetation.

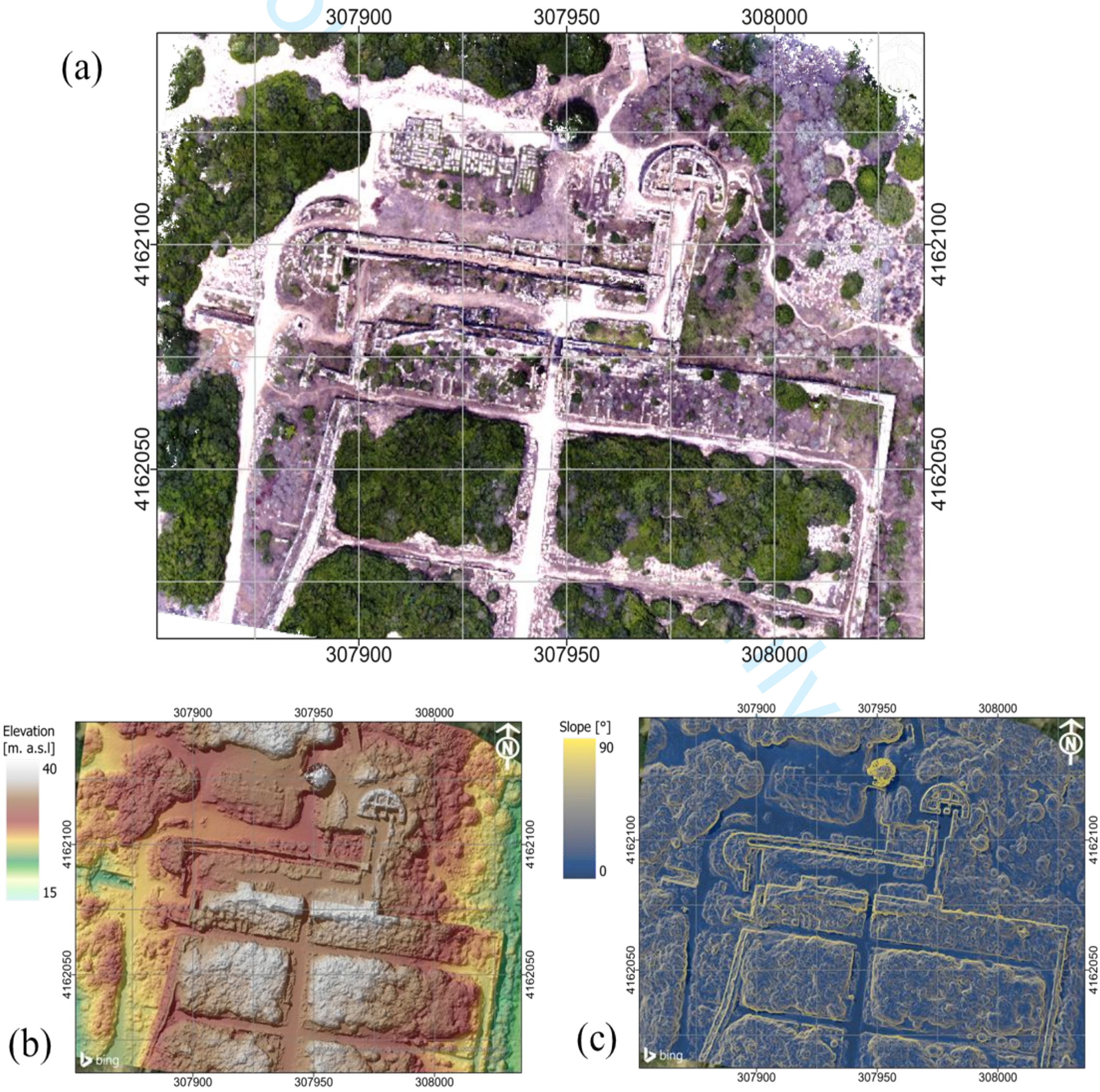

Figure 3. Northern fortifications overview. Digital Surface Model resulting from an aerial survey performed through UAV photogrammetry: RGB colored (a), elevation (b), and slope (c).

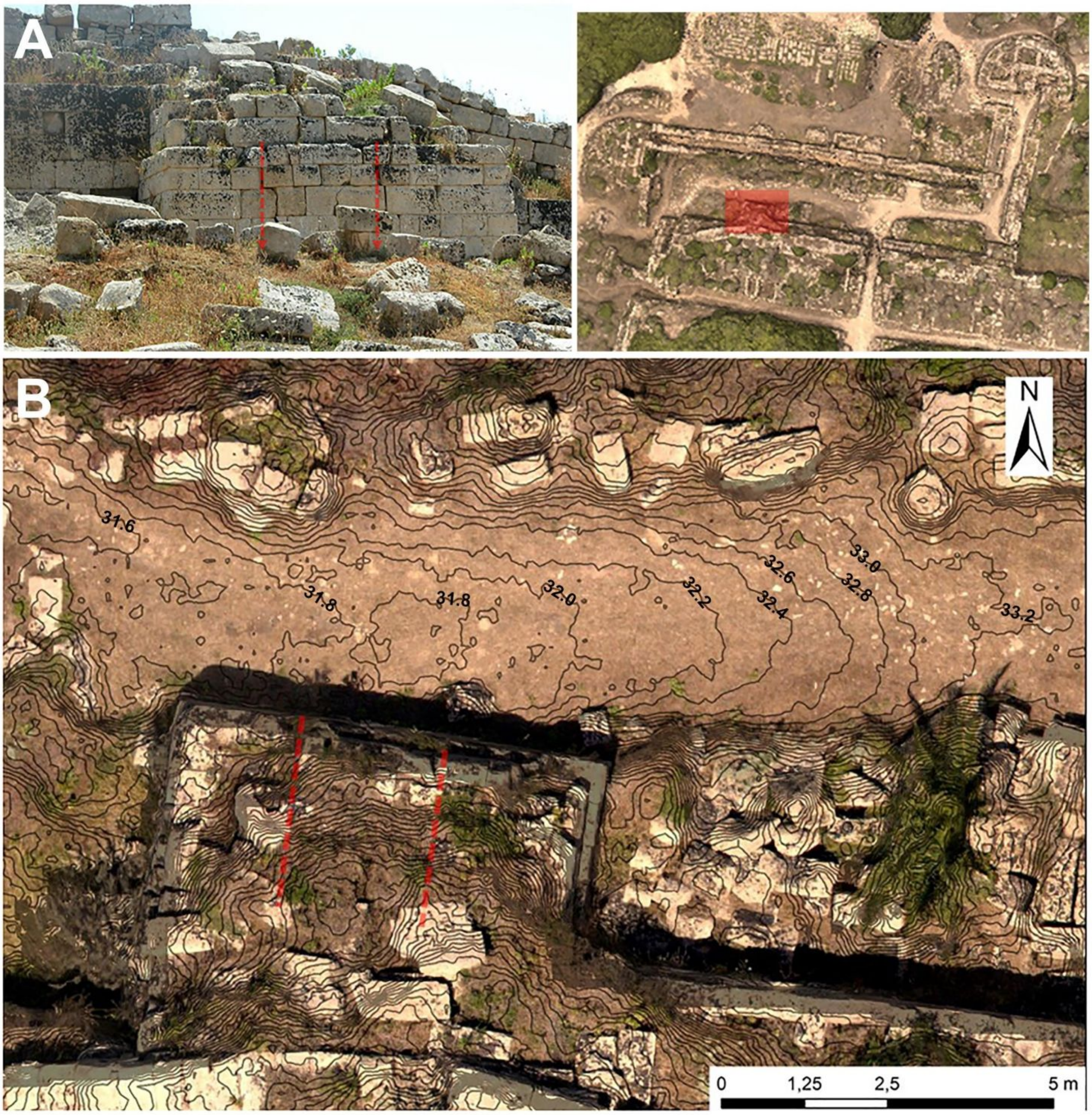

Figure 4. Northern fortifications: square tower along the external wall axis. The typical pattern cracking due to differential subsidence on defensive: A) the picture of a sector of the defensive wall, the main cracking system in red; B) the Orthophoto combined with DSM shows the depression at the bottom of the masonry.

There are several software packages available that can be used to create digital surface models and orthomosaic from the drone captured photographs. In this study, we used Agisoft Photoscan software which applies Structure from Motion (SfM) photogrammetry to process raw images from the drone. Agisoft Photoscan is a commercial software able to create 3D content from still images. It is capable of interpolating digital images creating high resolute scaled and georeferenced three dimensional models from them. Tests have revealed that Photoscan excels in processing aerial frame imagery which makes it very suitable for these studies.
The first step in the program's procedure is called Structure from Motion (SFM). The first results obtained through the applied procedures have been on one side the creation of orthophotos – extremely important for the bi-dimensional redesign – and on the other the creation of a 3D polygonal mesh, useful for rebuilding the whole archaeological site in its three dimensions in a virtual environment. Figure 3 shows the resulting high-resolution cloud and DSM model of the investigated area.

Numerous fractures, dislocations and collapse kinematics were detected along the Grand Gallery sector already in the first campaign of 2008. The causes of these failures are not always clear and could be attributed to various causes such as site effects of ancient earthquakes (Guidoboni et al., 2002), differential structural subsidence due to the geological setting of the area (Amadori et al., 1992) or damage caused by Carthaginian war activity (1st Punic War) in the III century BC.
Selinunte was built on sedimentary terrains from the Pleistocene age, constituted by sands, sandy clay and clays with levels and lens of Marsala Calcarenites (Ruggeri et al., 1977). These *facies* are subject to chemical weathering and mechanical erosion, also correlate to irregular karst process at subsurface levels, developing slight depressions in the ground as a form of a collapsed natural ancient landscape, largely responsible for extensive damage to the ancient walls. The high-resolution DSM map help us to discriminate the effect of this phenomenon. Figure 4 shows an example of the pattern of the typical cracks spreads on the defensive walls due to differential subsidence; whereas Figure 5 illustrates severe frontwards movement due to the same process.

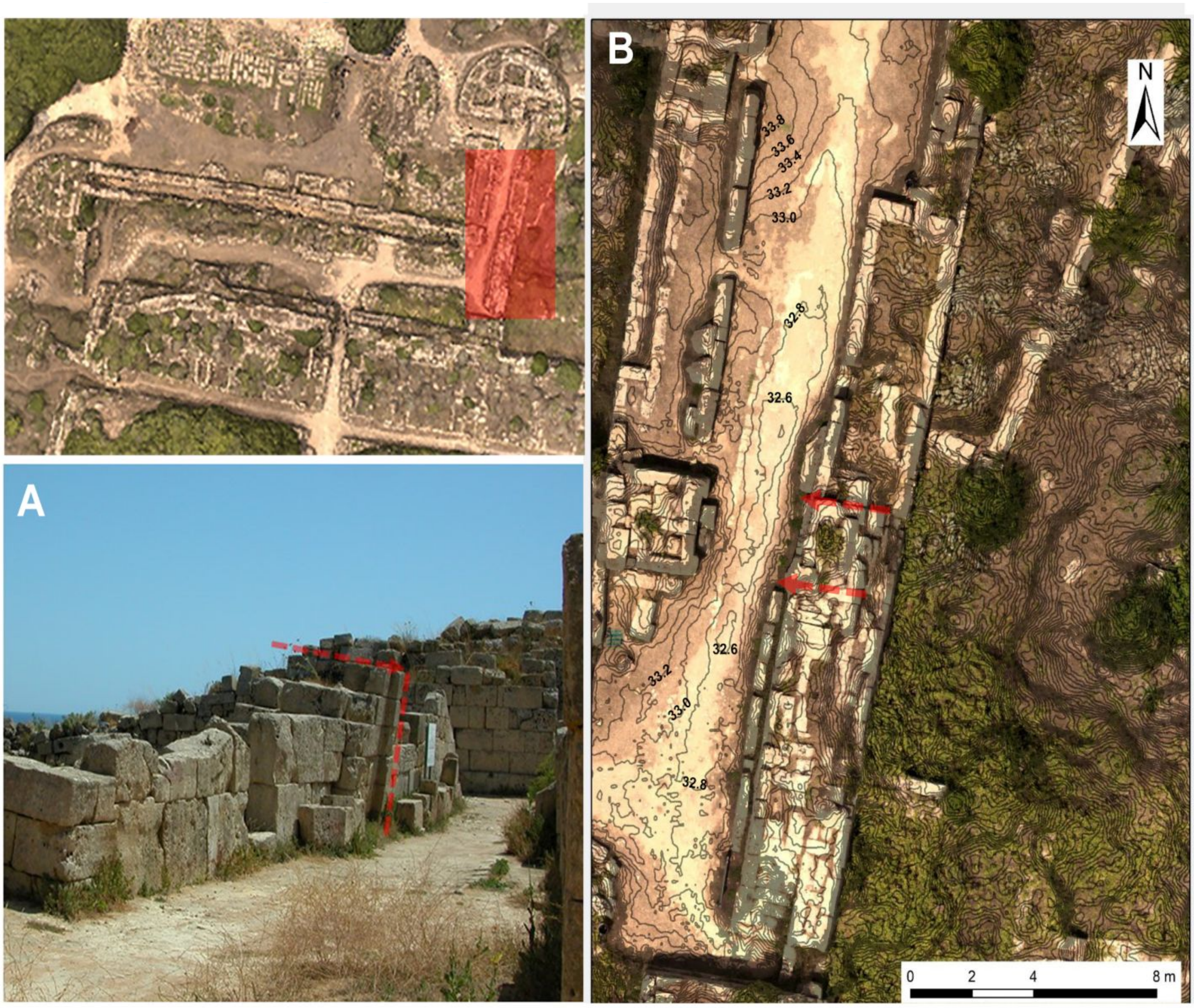

Figure 5: Gate XVIII sector. The frontwards movement of the inner defensive wall: A): the picture of an inner sector of the defensive wall, the slipping movement in red; B) the Orthophoto combined with DSM shows the depression at the bottom of the wall.

3.2 Model by TLS

The terrestrial laser scanning survey was executed using a Z+F Imager® 5010c laser scanner (Zoller & Fröhlich, Wangen im Allgäu, Germany). Investigations were carried out according with the method of phase comparison using a wavelength of 1.5 µm, therefore a laser of class 1 following the UNI EN 60825-1 code.

Ninety scans were performed to cover as many parts as possible of the walls and surrounded area, with particular attention to overlay some targets of each acquisition with the previous one. The sensor was set to obtain a resolution beneath 4 mm for the distance of 10 meters, combining the acquisition of high dynamic range (HDR) panoramic pictures with a resolution of 80 Mpixel for the colorimetry of the point clouds. Nevertheless, during the campaign activities, it was noted that large zones are characterized by spontaneous vegetation right near the objects to be detected. This vegetation produced high noise in the point clouds; therefore, in the pre-processing phase, using the JRC 3D Reconstructor software (JRC 3D, 2012), all scans were filtered and the vegetation points were manually eliminated from the clouds.

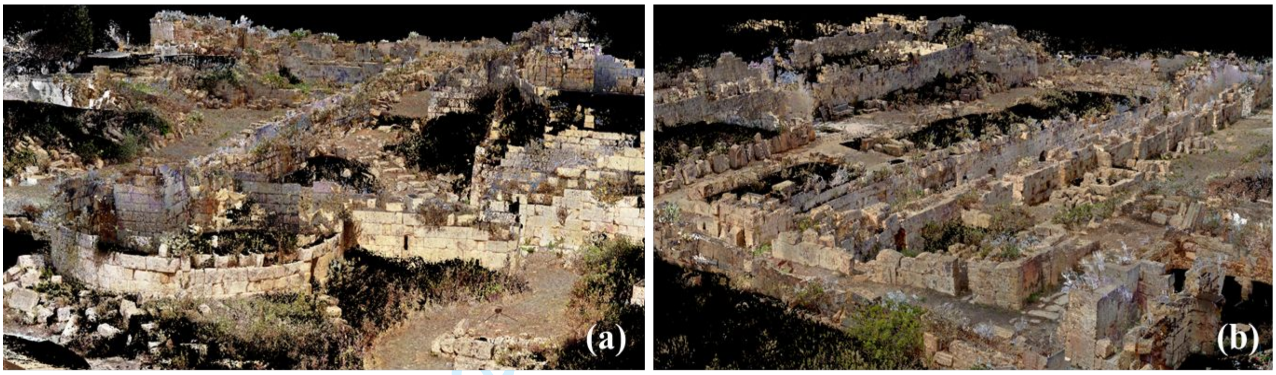

Figure 6. Grand Gallery sector. Views of the three-dimensional model of the northern part of the Acropolis obtained from the alignment of the ninety scans carried out by terrestrial laser scanning: looking from the south-west towards north-east (a) and in the opposite direction (b).

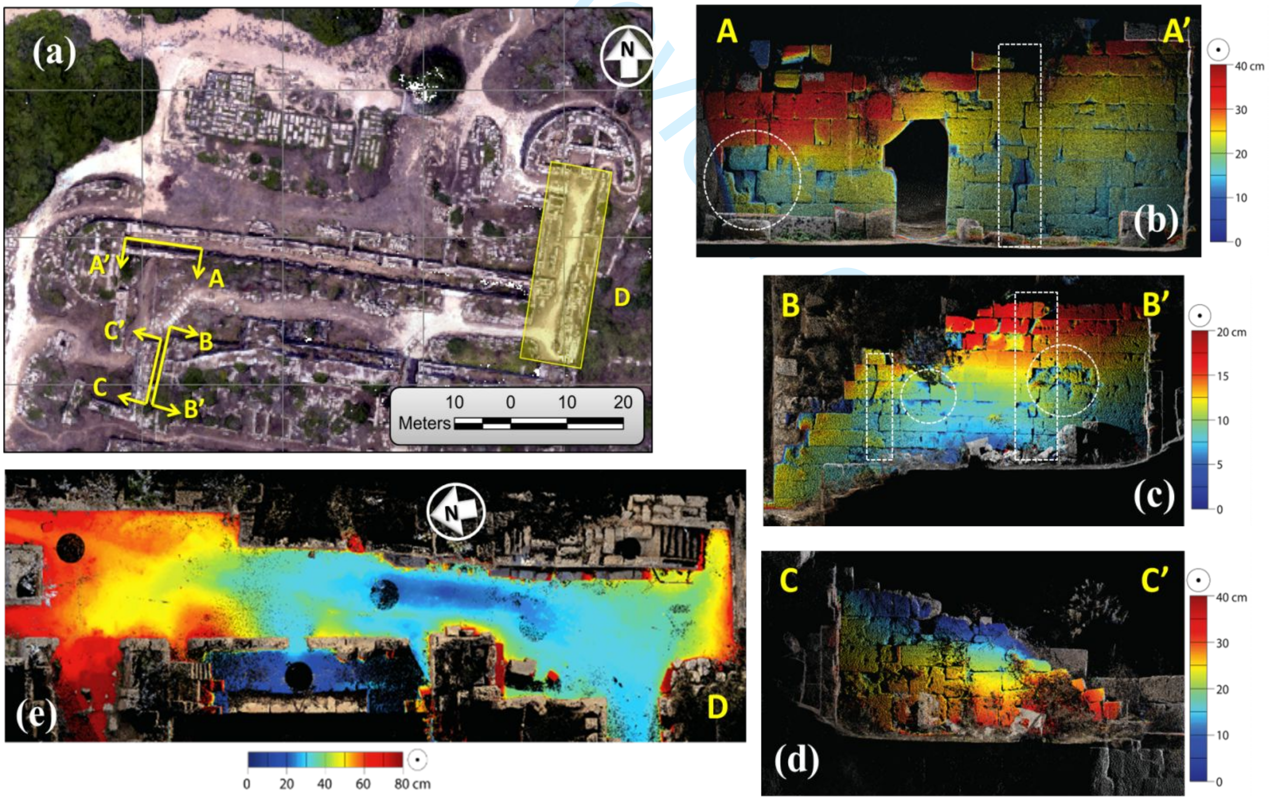

Figure 7. Geometrical anomalies on the point clouds obtained by terrestrial laser scanning for the elements indicated on the map (a). Residuals for the walls of the fortifications with reference to the vertical best-fitting planes: section AA' (b), section BB' (c), section CC' (d). Residuals for the passage in correspondence of the Gate XVIII (yellow rectangle D on the map) with reference to the horizontal plane (e).

Afterwards, the alignment of the single scans was necessary to obtain the whole 3D model, thereby introducing an intrinsic error in the model due to this processing phase. To combine the large series of scans through a unique reference system, initially a scan to scan pre-alignment was performed with point pairs picking, i.e. setting at least three reference points detected in both reference and mobile (free to shift and rotate) clouds. During this processing phase the mean registration error was limited to a value of about 2 mm. Afterwards a bundle adjustment was implemented to avoid significant distortions of the 3D model (Pfeifer & Briese, 2007). At the end of the processing phase, we obtain a mean registration error of about 1.68 cm. Figure 6 shows two views of the observed area through the arrangement of all point clouds.

Geometrical anomalies on the fortifications are mapped through the residuals (cf. sections AA', BB' and CC' in the Figures 7a, b, c, d), which were calculated as the distance between the point cloud and the vertical plane best-fitting the representative points of the investigated surface (Costanzo et al., 2015; Fais et al., 2018). In particular, the analysis on different portion of the fortifications showed significant inclinations of the walls respect to the vertical, with higher values of the slope between 2 and 4 degrees (i.e., residuals between 10 to 20 cm for height of about 3m). In different parts of the fortifications, through-cracks with openings of few centimeters go across with continuity the wall from the base to the top (e.g., see rectangles with dashed line in the Figures 7b, c). Moreover, it can be noted in the same figures the disintegration of the original mortar and a high degradation of the ashlars in limestones stone detectable on some part of the wall (e.g., see circles with dashed line in the Figures 7b, c).

In addition, the residual was calculated with respect to the horizontal plane for the passage at north-east, that from the North Gate leads to the Gate XVIII and then to the most advanced watchtower (cf. yellow rectangle in the Figure 7a). The analysis of the residuals shows the zone in its correspondence with elevation lower than 30 cm respect to the surrounded area (Figure 7d), as already detected through the model carried out by aerial photogrammetry; this phenomenon is probably due to an instability of the slope on which the passage insists.

3.3 Combined model

The TLS and UAVP provide complementary information: the first one returns very high resolution data and details on the vertical man-made elements; whereas, the second one allows to cover any spatial gaps and a wider area. For these reasons, the 3D model of the northern part of the Acropolis was obtained, including the terrain and manmade elements, by combining laser scanning that focused on perpendicular point clouds with UAV photogrammetry data that focused on the planar point clouds.

To achieve this goal, after a pre-alignment with point pairs picking taking as reference the point cloud by UAVP, because this has been geo-referenced through all the acquired GCPs, the relative position of the laser scanning and photogrammetry results was determined via the ICP algorithm implemented in Cloud Compare software (CloudCompare, 2020). The process was continued until the difference between the Root Mean Square errors (RMS) between two following iterations fell below a given threshold (10^{-5}). The final RMS between the two point clouds, calculated on over 1.5 million points and considering an overlap of 100%, results in 4.6 cm. The combined model is shown in the Figure 8; different views are reported considering the three point clouds: that obtained by UAVP photogrammetry (Figure 8a, d, g), that by laser scanning (Figure 8b, e, j) and the integrated one (Figure 8c, f, k).

To assess the most marked differences between the two point clouds, a comparison was performed through the M3C2 algorithm. This algorithm permits to make a direct comparison between two point clouds. Practically, it consists in two steps: the surface normal estimation and orientation in 3D at a scale consistent with the local surface roughness; then, the measurement of the mean surface change along the normal direction with explicit calculation of a local confidence interval (Lague, Brodu, & Leroux, 2013).

In Figure 9, the point cloud has been colored according to the signed distance between the two models. The results show significant differences in correspondence of the vertical elements, as can be expected because with the UAVP photogrammetry the information is bounded at the base and top of the walls. At the same way, an appreciable distance is detectable in the zones where the point clouds are characterized by a lower density of points and, then, the assessment of the surface normal could be less accurate, i.e. to the margins of the survey area or where the vegetation produced high noise. Instead, the difference is practically negligible in the parts characterized by bare soil.

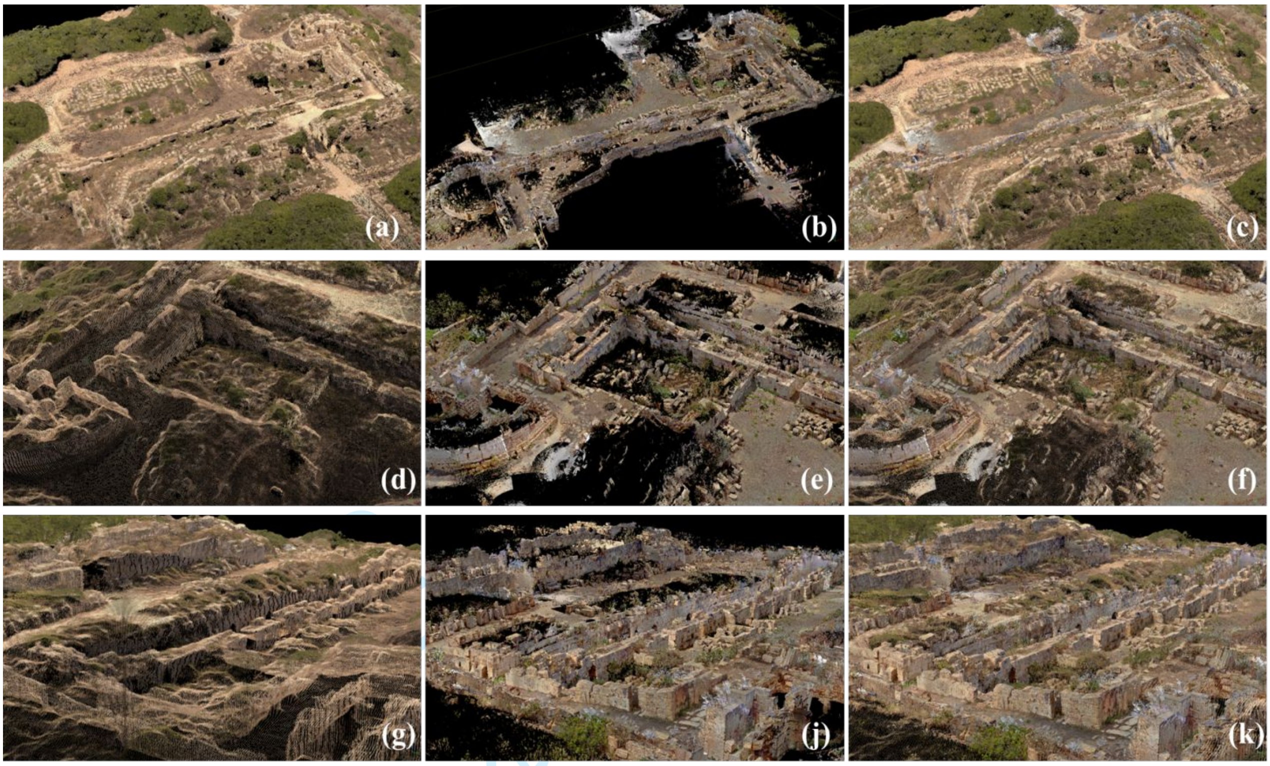

Figure 8. Comparison among the different point clouds: that obtained by aerial photogrammetry (a, d, g), that by terrestrial laser scanning (b, e, j) and the combined ones after the co-registration process (c, f, k).

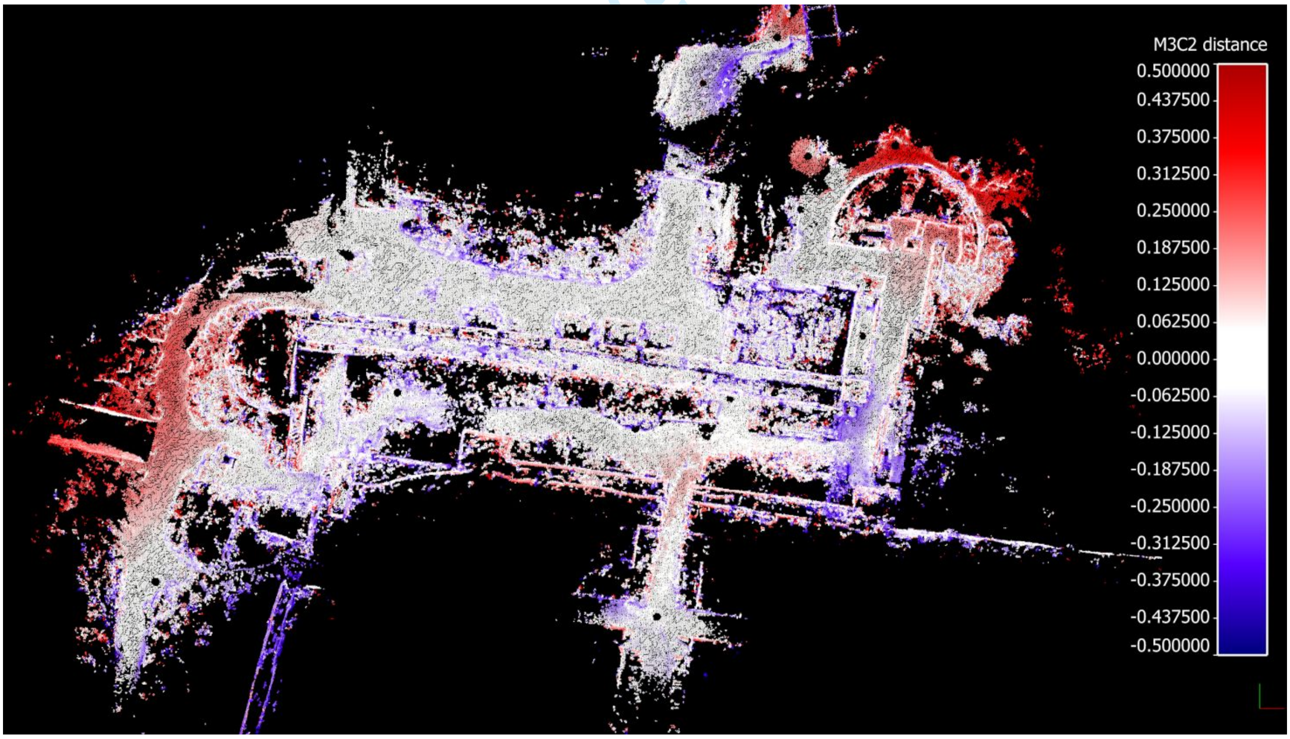

Figure 9. Differences between the point cloud obtained by terrestrial laser scanning and that by UAV photogrammetry. The distances between the point clouds are obtained by the M3C2 algorithm and the colours indicate the distance between the two point clouds in meters.

4. Conclusions and General Remarks

In this work we have presented the application of TLS and UAVP techniques for the detailed analysis of the most important structures and the landscape in the Selinunte's Acropolis. TLS and UAVP are techniques capable of providing useful data for accurate diagnosis and current state of the art of a study area. The work focuses on the data integration strategy for the 3D modeling of buildings and cultural heritages. Specifically, we have focused our investigations on the northern part of the Acropolis, where a previous investigation (Pannaccione Apa et al., 2010) recognized the damage suffered over time due to human causes and natural deterioration, as well as repairs made in ancient times and current restorations.

We show as the integration of data acquired independently by these two techniques can provide useful dataset for the 3D reconstruction, overcoming the intrinsic limits of the individual techniques. Indeed, while TLS allows to collect data of the highest precision on the vertical direction (more difficult to achieve through an aerial survey), UAVP permit an easy extension of investigations to areas that cannot be reached by TLS. Generally speaking, TLS and UAVP provide complementary information: the first one returns very high resolution data and details on the vertical man-made elements whereas, the second one allows to cover any spatial gaps and a wider area.

One of the main results of this work is the definition of a clear procedure for the TLS and UAVP data acquisition, processing and integration, as summarized in the workflow of Figure 2. The careful planning and execution of the TLS and UAVP surveys, together with a proper processing and fusion of the acquired data could allow the realization of a complete and robust 3D model of the investigated area.

The application to the Selinunte's Acropolis allowed to highlight and measure with high accuracy fractures, dislocation, inclinations of walls, depressions of some areas and other interesting observations. Several hypotheses have been made on these failures as site effects of ancient earthquakes, like those documented in Guidoboni et al. (2002), or differential structural subsidence due particular geological condition of the foundation soils. However, we believe that the data so far collected, aren't enough to clarify the causes of the kinematics and must be considered basically as important starting points for future investigations.

The data and results presented in this paper are only a little part of a long-term research project focused on the Selinunte's Acropolis. The ambition of the project is the analysis and survey of the perimeter fortifications surrounding the entire Acropolis, in order to obtain more information on the geological evolution and geophysical events that interested this sector of the archaeological area. The study presented here has given useful experience with the combination of these integrated scanning techniques for archaeological purposes. The results demonstrate that can within a short amount of time capture complex areas with high survey precision measurement, also that the combined scanning techniques are promising but that new studies must be carried out in order to fully understand its real potential.

The next campaigns, scheduled within the next two years, will follow the same model of field data collection technique, from traditional archaeological survey to applied geophysical and engineering techniques. We plan to applied these non-invasive scanning techniques also in other sectors of the Selinunte Acropolis in order to improve the analysis on the cracks and dislocations of the defensive walls and their development.

We also plan to integrate our investigations with other techniques (Scudero et al., 2018) like passive and active seismic methods able to assess local seismic response due to the specific litho-stratigraphical and morphological conditions of a site (Martorana et al., 2018a, 2018b). The identification of seismic site effects will be useful in establishing how it may have contributed to the injuries and collapses suffered by the buildings of the acropolis. To this end, a project of recordings of ambient noise (microtremors) has already started and will be expanded in the future. It provides measurement points that will be regularly distributed over the entire acropolis area, but more concentrated around the North Gate. Proper application of the Horizontal to Vertical Spectral Ratio (HVSR) method, applied to microtremor recordings, will allow to estimate the distribution of fundamental frequencies of site amplification (D'Alessandro, Luzio, Martorana, & Capizzi, 2016). Another important contribution to the local seismic response may be given by the detailed seismic characterization of the studied area, by using MASW techniques to determinate of the S wave velocity distribution.

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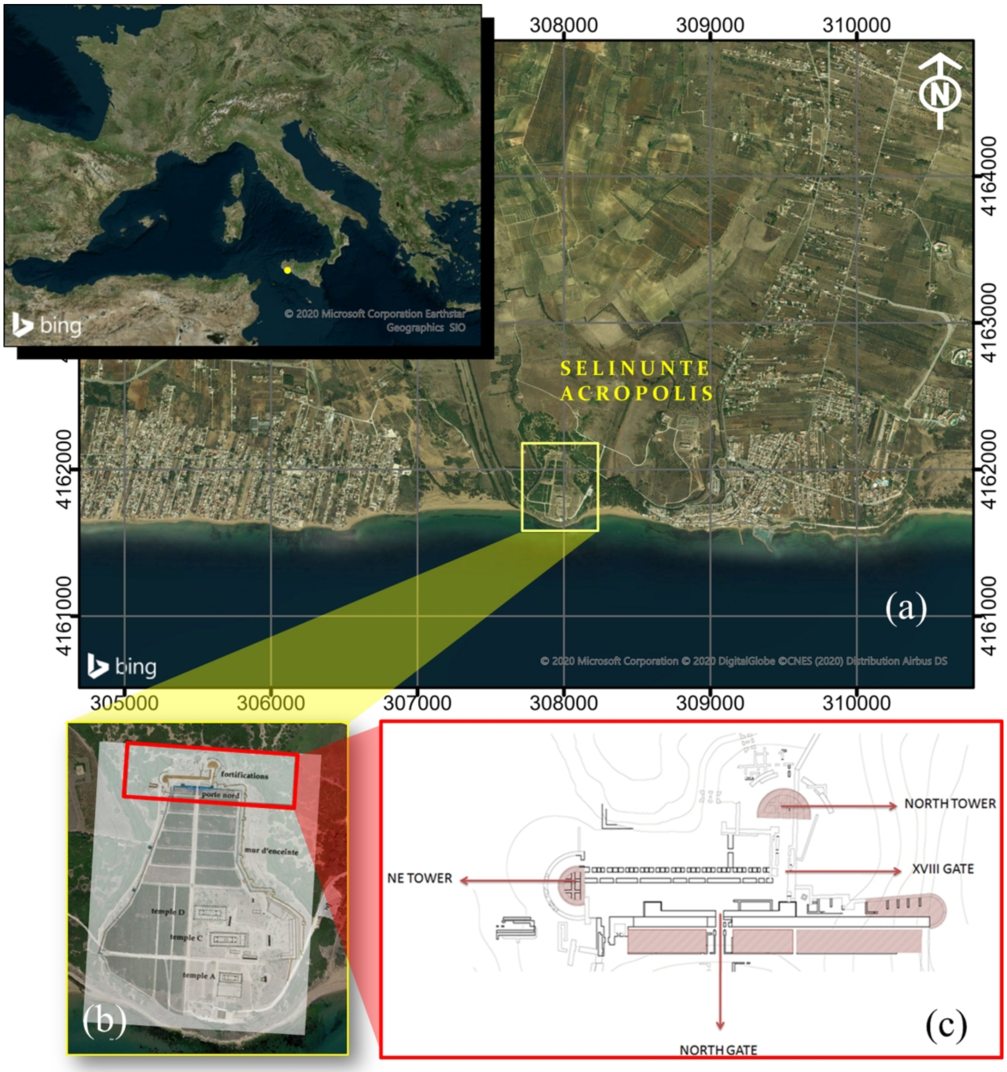

Figure 1. Location of the Archaeological Park of Selinunte in the Italian territory and of the Acropolis respect to the South-Eastern coastline of Sicily with general plan of the Acropolis (a). The test site is framed in the red rectangle: (c) detail of the North fortifications and the position of North Gate, Grand Gallery, NW and N Towers and Gate XVIII (Bassani & Besana, 2015; Tav. 04).

Figure 2. Workflow of the survey and processing of data using terrestrial laser scanning and UAV photogrammetry.

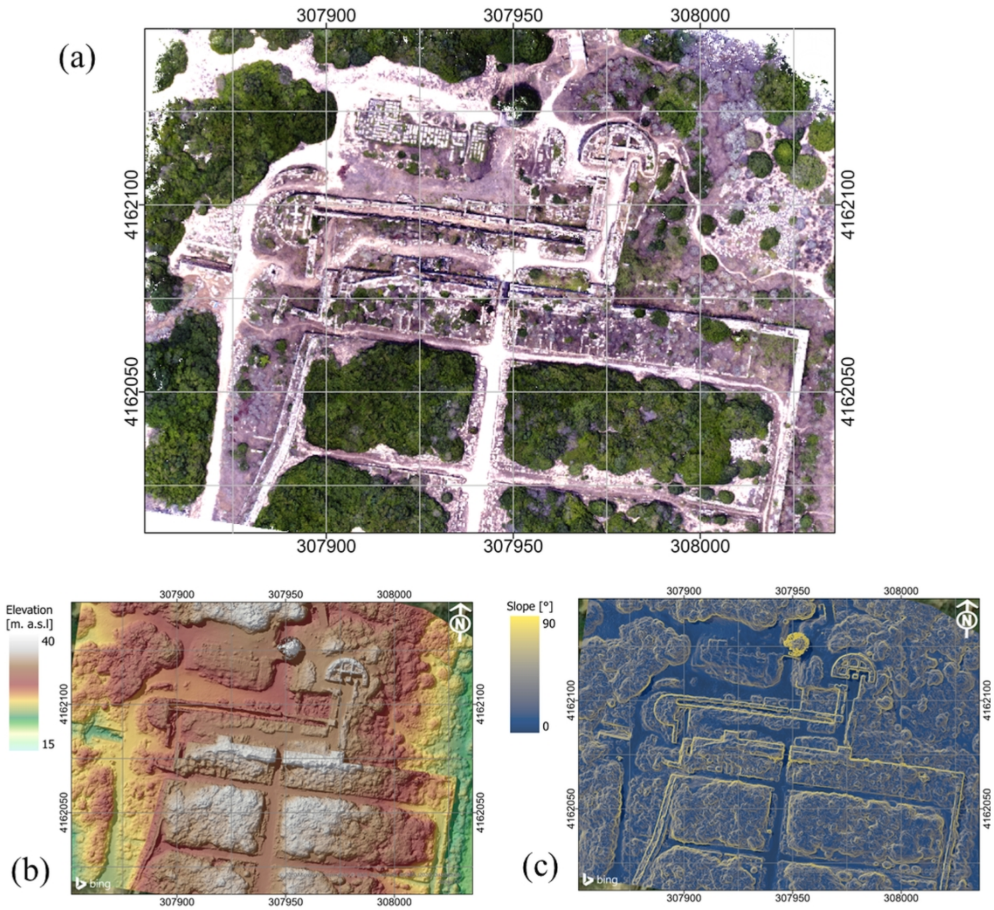

Figure 3. Northern fortifications overview. Digital Surface Model resulting from an aerial survey performed through UAV photogrammetry: RGB colored (a), elevation (b), and slope (c).

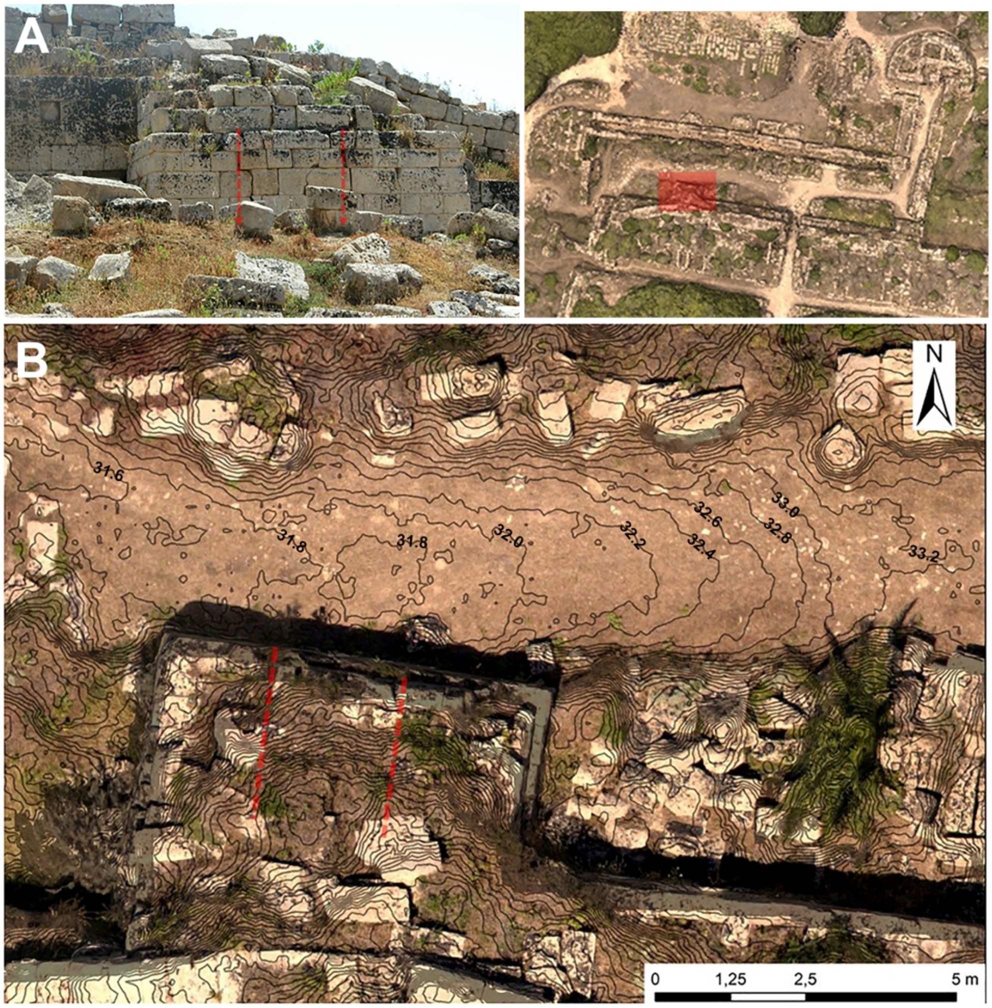

Figure 4. Northern fortifications: square tower along the external wall axis. The typical pattern cracking due to differential subsidence on defensive: A) the picture of a sector of the defensive wall, the main cracking system in red; B) the Orthophoto combined with DSM shows the depression at the bottom of the masonry.

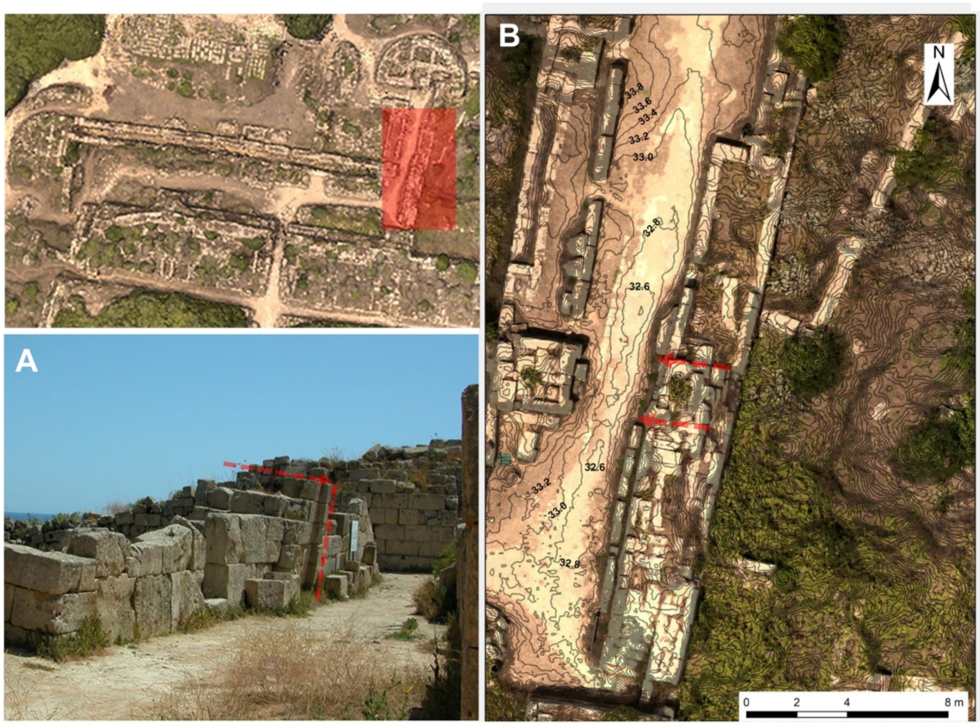

Figure 5: Gate XVIII sector. The frontwards movement of the inner defensive wall: A): the picture of an inner sector of the defensive wall, the slipping movement in red; B) the Orthophoto combined with DSM shows the depression at the bottom of the wall.

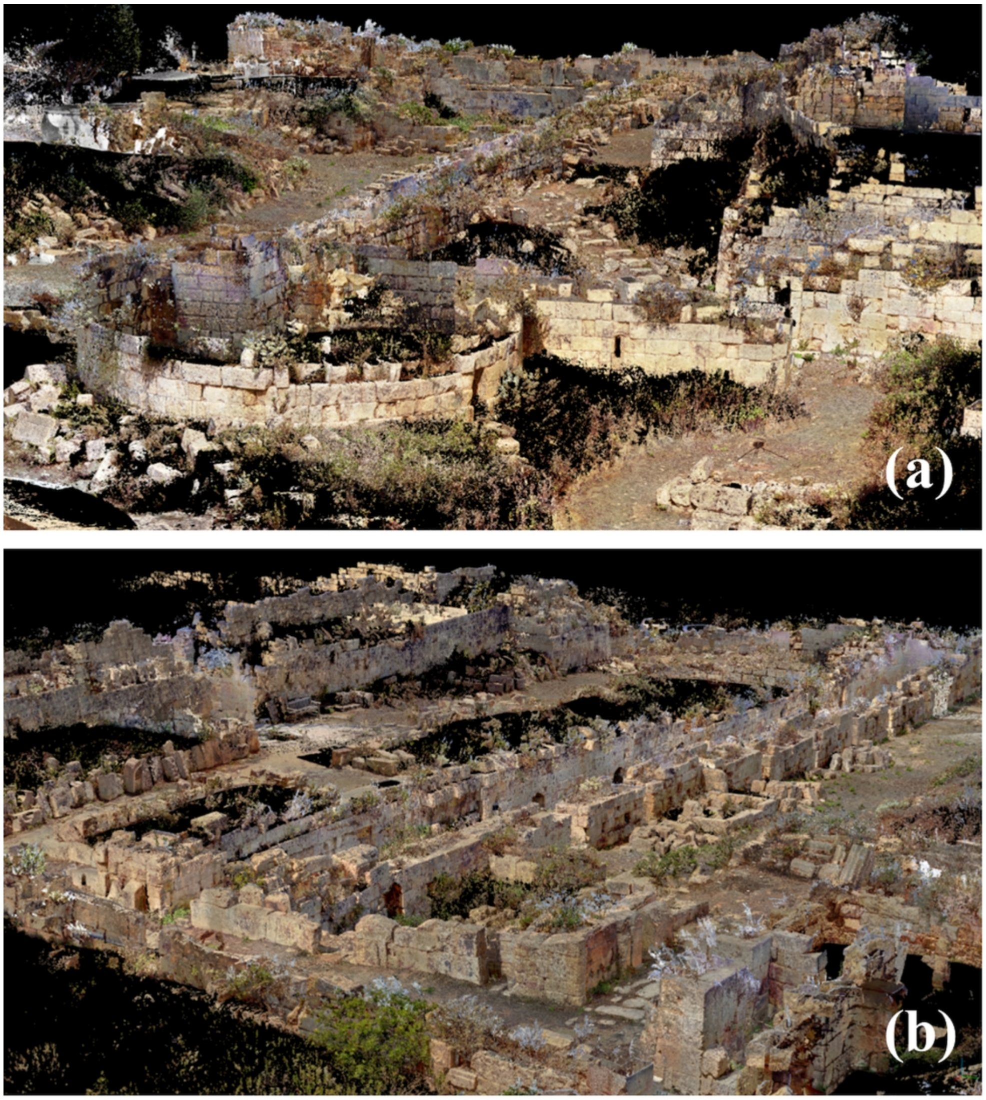

Figure 6. Grand Gallery sector. Views of the three-dimensional model of the northern part of the Acropolis obtained from the alignment of the ninety scans carried out by terrestrial laser scanning: looking from the south-west towards north-east (a) and in the opposite direction (b).

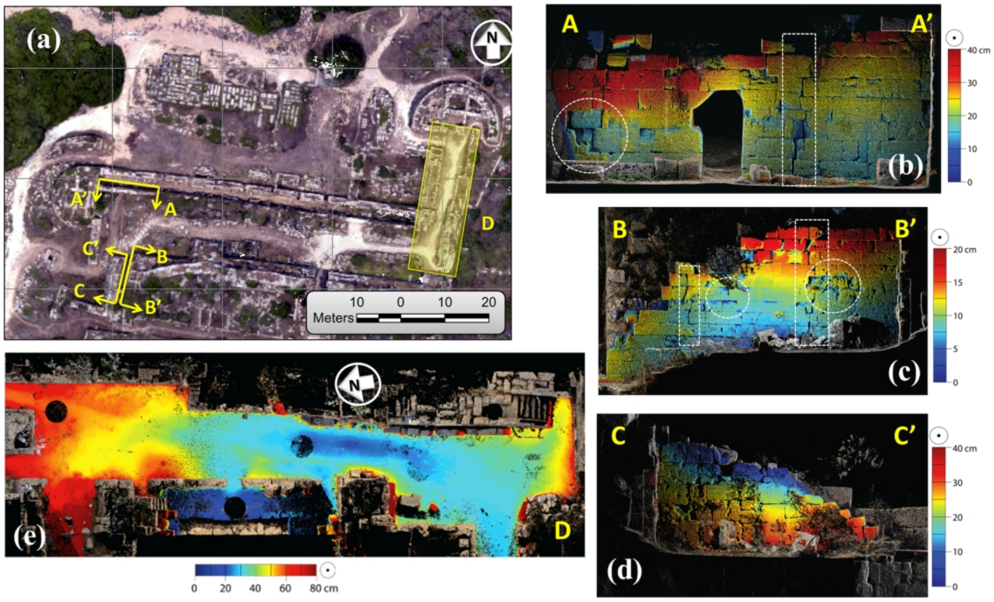

Figure 7. Geometrical anomalies on the point clouds obtained by terrestrial laser scanning for the elements indicated on the map (a). Residuals for the walls of the fortifications with reference to the vertical best-fitting planes: section AA' (b), section BB'(c), section CC' (d). Residuals for the passage in correspondence of the Gate XVIII (yellow rectangle D on the map) with reference to the horizontal plane (e).

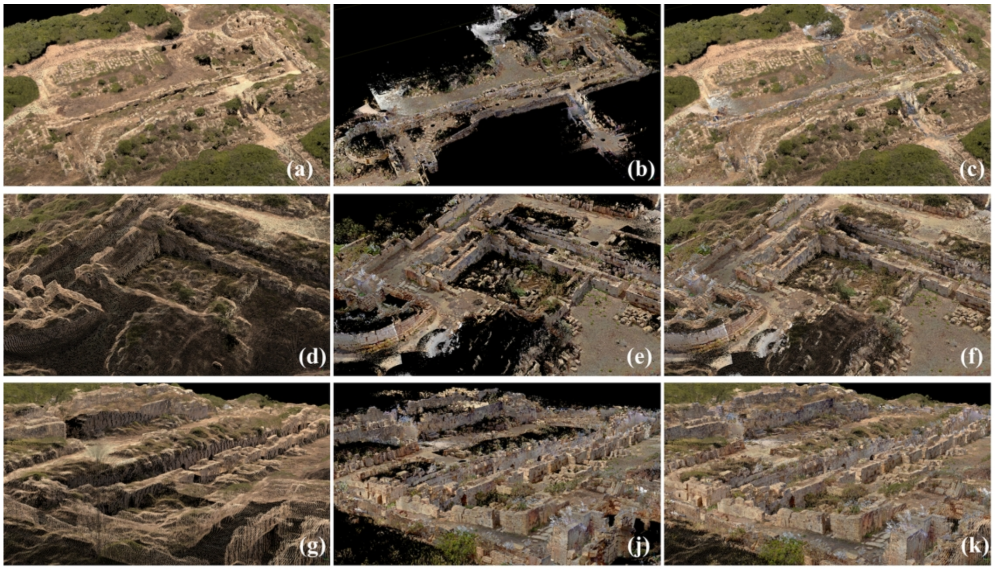

Figure 8. Comparison among the different point clouds: that obtained by aerial photogrammetry (a, d, g), that by terrestrial laser scanning (b, e, j) and the combined ones after the co-registration process (c, f, k).

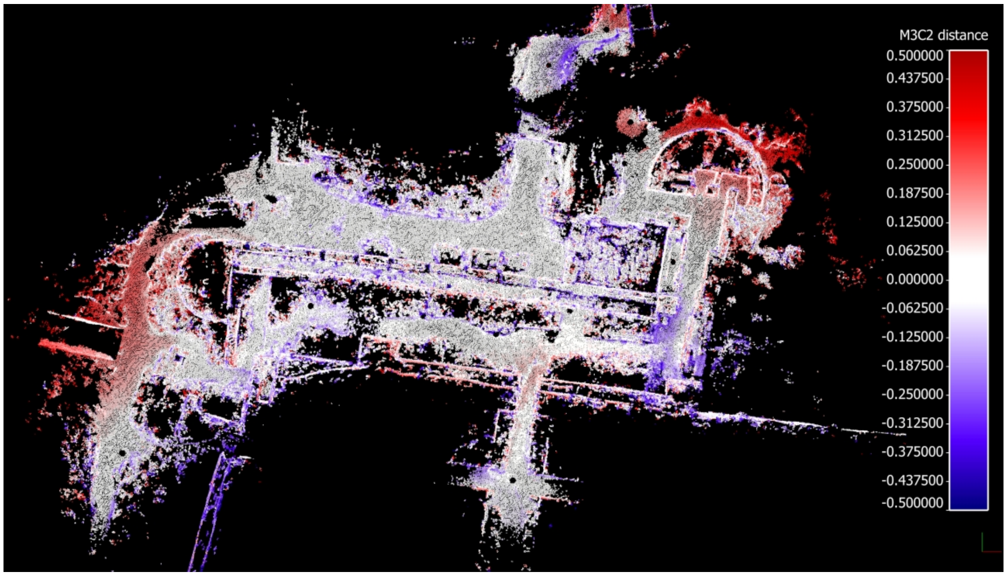

Figure 9. Differences between the point cloud obtained by terrestrial laser scanning and that by UAV photogrammetry. The distances between the point clouds are obtained by the M3C2 algorithm and the colours indicate the distance between the two point clouds in meters.