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A multidisciplinary non-invasive approach in geoarchaeology conducted on the archaeological area of Selinunte

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Abstract **– 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 (see e.g. [1]) as severe event, that is characterized by moderate-high energy (M=6.5) and significant epicentral and local macroseismic intensities (Io=X and I=VII-VIII of the MCS scale). Nevertheless, some studies (e.g. [2]) 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 produce collapse in some temples of Selinunte. In this framework, we propose the use of non-invasive approaches in geoarchaeology for detecting and measuring structural damages in walls and foundations of Selinunte Acropolis, in order to identify any effects due to historic earthquakes. The methodology consists of an integration of landscape analysis, remote sensing and geophysical methods useful for dating important ancient seismic events. The intents of this multidisciplinary research are: 1) the detailed analysis of the most important structures and the landscape, also to assess kinematics behaviour of the masonry segments and their defects (cracks, disintegration of the original mortar, replacement of ashlars, etc.) and 2) the analysis of the seismic site response in order to assess potential amplification phenomena on the ground motion. The preliminary results seem to show significant residuals on the walls on the East side of the Acropolis, where also the geological and stratigraphical setting provide amplification effects in correspondence of frequency range typical of the earthquakes and for manmade structures.**

I. INTRODUCTION

The Selinunte Archaeological Park, is currently the largest archaeological area in Europe, covering 270 hectares, that includes temple architectures (on the eastern hill and inside the Acropolis), necropolis and impressive fortifications surrounding the Acropolis. The promontory where the Acropolis stands has the first levels of occupation ascribable to the Mesolithic period 8000-6500 BC. Selunute Magno Greca was founded by colonists of Megara Hyblaea. According to Thucydides (Θουκυδίδης) its foundation dated in 628/627 a.C .; to Diodorus Siculus (Διόδωρος) in 651 BC. In 409 BC. Carthage destroys Selinunte; in 408-7 BC Ermocrates, tyrant of Syracuse, begins reconstruction and strengthening of fortifications; in 397-2 B.C. the tyrant Dionysius I completes advanced protective works; in 250 BC (I Punic War) Carthage dismantles and transfers the inhabitants of Selinunte to Lilibeo (loc. Marsala). In the centuries III - V d. C. there is evidence of a Christian occupation and in the VIII century, of one Byzantine. In the X-XI centuries Selinunte is just a small village; damaged by a strong earthquake is definitively abandoned. In the sixteenth century, is rediscovered by Tommaso Fazello [3]. Beginning in 1823, the archaeological excavation season opened (Cavallari, Hulot, Fougère, Salinas, V. Tusa, Mertens, S. Tusa) and presently continues with the systematic excavations directed by C. Marconi (NY University). An INGV archaeosismological team also works on this site since 2008 [4]. In 2008 INGV launched an archaeological survey with non-invasive investigations in the Acropolis area of the Archaeological Park of Selinunte based on a a data gathering survey along the northern fortifications in order to detect and characterize, where possible, the type of damages sustained by the defensive walls. 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. 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. The aim of this campaign has been to implement a new non-invasive approach by geophysical and proximal remote sensing methods, to integrate the usual archaeological survey on identification ancient natural disaster events. The geodetic technologies are an effective tool for non-invasive analysis in order to produce a reading and an accurate diagnosis of the current state of art of the northern fortifications (selected test-site area). The collected data set, processed and integrated together allowed us to make use of a series of fundamental information for a correct chronology of: 1) where possible: events that produced damages; 2) damage classification and typology; 3) support the chronological wall reconstruction phases and 4) history of its architectural evolution.

II. MATERIAL AND METHODS

A. Aerial Archaeology

Remote Sensing Aerial Archaeology is a sub-field of Remote Sensing, 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 superior results in non-destructive archaeological studies. Usually in archaeology, it is used as a means to locate and verify ancient remains 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 lays 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 [5, 6]. Unmanned aerial vehicles (UAVs) or drones have become widely available for use in a broad range of disciplines. They offer multiple advantages over traditional field work or high-altitude remote sensing techniques, in that they enable the reconstruction of three dimensional models of inaccessible or unsafe outcrops, and can bridge the spatial scale gap in mapping between manual field techniques and airborne, high-altitude remote sensing methods. 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 provide comprehensive tools for manage all the aspect of the spatial information science. Digital Surface Model (DSM) and digital orthophotos provide to extract information on the structural walls and terrain elevation profile. In this study, we used a DJI Phantom III Professional drone (quadcopter) with a mounted 12 Mega Pixel digital camera. Before conducting 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 a 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, and mapped in total an area of about 0.3 km2, we focus the mapping on the North door and defensive walls. The acquisition of field data requires the determination of several control points on the ground, known as GCPs (Ground Control Points). Subsequently between 15 and 20 points, 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. 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 1 shows the resulting high resolution cloud and DSM model of the investigate area.

B. Terrestrial laser scanning (TLS)

A terrestrial laser scanning (TLS) survey was performed to obtain accurate and complete 3D model. Combining the distance with the two internal angle measurements of the rotating mirrors of the scanner, a spherical coordinate system centred on the sensor can be defined and any point on the surface of the object can be recorded using this spherical coordinate system. The set of coordinates representative of a scanned object is a so-called point cloud. Generally, the scanner allows to detect for each recorded point two kinds of information: the position, as set of coordinates, and the reflectance, as ratio between the emitted and reflected phases (or energy) of laser wave.

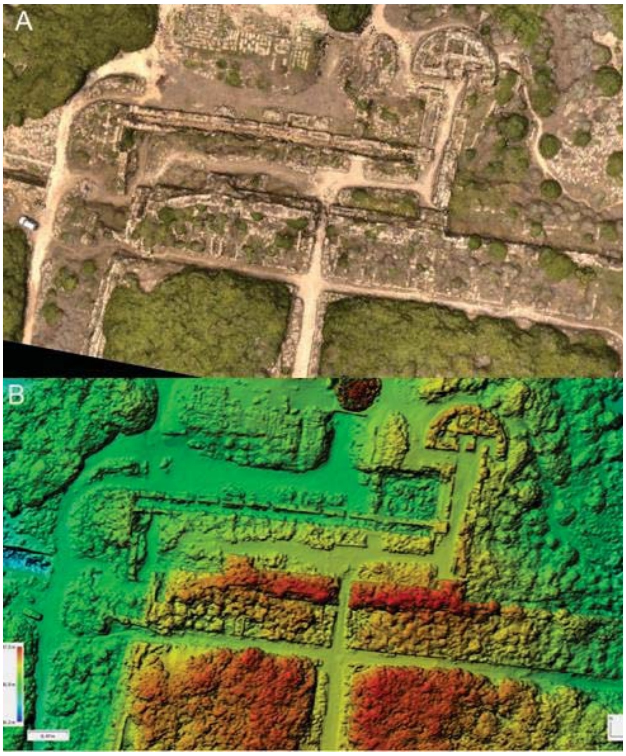

Fig. 1. The high resolution cloud (a) and the resulting DSM model (b) of the investigate area from the aerial survey.

In the present work the TLS survey was executed using a Z+F Imager® 5010c laser scanner (Zoller & Fröhlich, Wangen im Allgäu, Germany) based on the method of phase comparison with wavelength of 1.5 µm, therefore a laser of class 1 following the UNI EN 60825-1 code. To detect the wide area was needed 90 scans. The sensor was be used imposing an accuracy beneath 4 mm for the distance of 10 meters, and combining the acquisition of high dynamic range (HDR) panoramic pictures with resolution of 80 Mpixel for the colorirmetry 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, which was removed by ad hoc techniques before starting with the manipulation of the data. Afterwards, an alignment of the single scans was necessary to obtain the 3D reproduction, thereby introducing an intrinsic error in the model due to this processing phase. To match the large series of scans in a unique reference system, initially a scan to scan pre-alignment was performed setting at least three reference points detected in both reference and mobile (free to shift and rotate) clouds, afterwards an interactive closest point algorithm was implemented to avoid significant distortions of the 3D model [7]. At the end of the alignment phase a mean error of about 2.5 cm was introduced in the model. Therefore, for a global point of view the entire 3D model were reconstructed (Figure 2.a), whereas for high-detailed considerations also the single point clouds were analysed (Figure 2.b). In the latter figure the residuals are shown respect to a vertical plane intersecting a portion of wall close to the eighteen door.

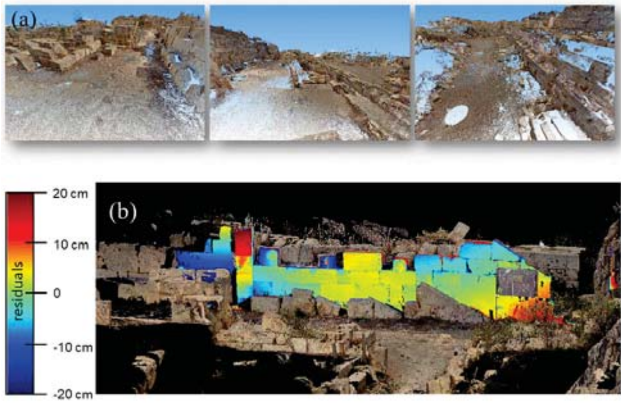

Fig. 2. 3D models by terrestrial laser scanning: (a, upper panels) views of the site and (b) residuals respect to an intersecting vertical plane on a portion of wall close to the eighteen door.

C. HVSR microtremor survey

The local seismic response is a modification in amplitude, frequency and duration of the seismic shaking due to the specific litho-stratigraphical and morphological conditions of a site. It can be quantified by the relationship between the seismic motion at the surface of the site and what would be observed for the same seismic event on a hypothetical outcrop of rigid rock with horizontal morphology. An assessment of it can therefore be useful to understand if it was the cause of the injuries and collapses suffered by the buildings of the acropolis. To make a preliminary assessment of the local seismic response of the area, 58 recordings of microtremors were performed [8], distributed over the northern area of the Acropolis of Selinunte, with a spacing of about 20 in the area of the North Gate and 30 m in the remaining part. The recordings have been elaborated with the HVSR technique, through which it is possible to estimate the fundamental frequencies of site amplification. Measurements were made using a sampling frequency of 256Hz, an acquisition time of 30 minutes, in order to perform a statistical analysis of each signal on 90 time windows of 20 seconds in length. This made it possible to analyze the temporal and directional trend of the seismic noise, obtain the HVSR spectral ratio, and then identify the central frequencies of the stratigraphically significant amplification peaks, following the SESAME criteria.

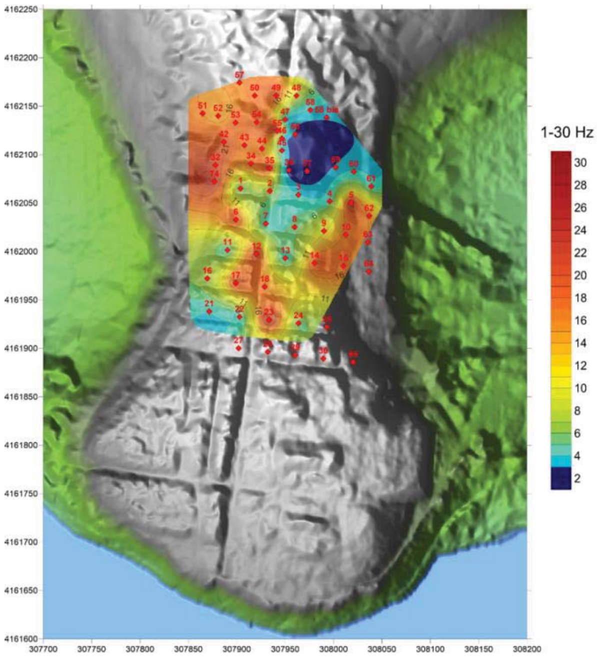

Fig. 3. Dominant frequency map of the investigated area.

III. PRELIMINARY RESULTS

The results obtained by the integrated application of laser scanning, photogrammetry, UAV's technologies and geophysical soil sensing, combined with more traditional and consolidated methods of documentation related to the archaeological research, can thus be expected to allow significant progress for research itself as well as result in the reduction of the time spent on acquisition of metrological data in the field and a considerable increase in precision, accuracy and adherence to the actual survey. The integration of Terrestrial Laser Scanning (TLS) and Remote Sensing Aerial techniques allowed to obtain comprehensive models of the ancient fortification walls by using each technique in the own optimal operating context. The morphological high-resolution analysis shows how some movements occurred on the defensive walls, the causes and the chronology are not clear yet. The distribution of the site amplification frequencies has been analyzed and the first preliminary results are presented below. The presence of a clear peak, at a frequency varying from 0.16 Hz at NE of the North Gate, and increasing up to 0.5 Hz towards S, can be caused by a basement that plunges towards NE. In addition, an area with a net change of frequency and a directionality towards SW, could be explained by hypothesizing a tectonic structure, but this hypothesis should be supported by other methods of investigation. Figure 3 shows the distribution of peak frequencies for the range between 2 Hz and 20 Hz. Significant peaks between 3-6 Hz (typical frequencies of an earthquake) were found only in some limited areas near the northern walls, which may have caused seismic amplification effects. In the remaining areas the resonance frequencies of the ground do not coincide with the resonance frequencies of the Acropolis buildings. Moreover C-Band Sentinel-1 (IW TOPSAR acquisition mode) SAR data along both the ascending and descending orbits were processed, using the DInSAR technique (Differential Synthetic Aperture Radar Interferometry. Unfortunately, the preliminary results don't show evidence of deformations in the archaeological area of Selinunte on the selected period of acquisition between 19 November 2016 and 13 July 2019. This study shows how the broad and varied spectrum of digital tools applicable to the field of cultural heritage can therefore provide a valuable support during key moments of the archaeological investigation.

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