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"COMBINED USE OF 3D METRIC SURVEYS AND NON-INVASIVE GEOPHYSICAL SURVEYS AT THE STYLITE TOWER (UMM AR-RASAS, JORDAN)"

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ABSTRACT
The Stylite Tower is part of the UNESCO archaeological site of Umm ar–Rasas (Jordan). It represents a *unicum* in its category and has a fundamental value for the Jordanian Cultural Heritage as a symbol and an emblem of Jordan's history and culture. The monument has evident signs of deterioration that appear in the form of substantial detachments of the plaster, water infiltration, erosion and fractures. Given the need to preserve this important ancient monument and for public safety reasons, a high–detail analysis of the Tower has been achieved through the realization of 3D geometrical surveys (Photogrammetry and Laser Scanner) and non–invasive geophysical surveys (using Ground Penetrating Radar Technique). The use of non–destructive testing techniques has provided encouraging results for the structural planning of diagnostic, consolidation and restoration activities.

1. INTRODUCTION

The archaeological site of Umm ar–Rasas is located 30 km south east to the town of Madaba in Jordan, north of the wadi Mujib, and it covers approximately 10 ha on Moab's plateau (Figure 1). The remains consist of a huge area, fortified by a massive wall that measures 158x140 m, on which numerous buildings are located and that once was a Roman Castrum (Figure 2a, b). Towards the northern part of the archaeological site both dwellings and sacred structures have been identified, which can be dated from the Byzantine to the Early Islamic period, up to the IX century A.D. (Figure 2a, b) [Piccirillo, 2008].

Umm ar–Rasas is identified with the ancient Kastron Mefaa, a place name known in biblical times that has been a military camp in Roman times, then an important Byzantine town and lastly a Christian city under Islamic rule. In 2004, it has been inscribed in UNESCO's World Heritage List.

FIGURE 1. Localization of the UNESCO archaeological site of Umm ar–Rasas (Jordan) on the satellite image ©2018 CNES/airbus from Google Earth™.

The most relevant religious complex is Saint Stephen's, by the name of the proto–deacon and proto–martyr to whom it was dedicated, a built–up area that had been developed between the VI and VIII century A.D. At least four communicating buildings formed it: the Church of the Tabernacle, which is the most ancient, the Bishop Sergius' Church with its baptistery and the funerary chapel to the front, the Saint Stephen's Church and the Church of the Courtyard, raised between the other three churches (Figure 2a, b).

The Stylite Tower, an exceptional example in its category, is located a kilometre and a half from the residential zone of the site towards the northern direction (Figure 2a, c, d). It does not have stairs and the only door is the one located at 14 m in height on the southern wall of a domed chamber on the top of the monument. In addition to the three windows on the other walls, a channel built inside the western wall connects the room with the base of the tower. On the outside, the room is decorated with a double–moulded ledge and with four columns at the corners formed by segments tied to the wall. The bases present the head of a raptor in relief. The capitals are decorated with interwoven geometric patterns. Originally, the tower was plastered, as testified by the traces still visible on the walls [Piccirillo, 1989].

From the general plan of the area, it turns out that the tower stands at the centre of a courtyard in a fortification on the highest terrace. At the southeast corner of the courtyard there is a small church flanked to the north by two intercommunicating rooms [Savignac, 1936; Piccirillo, 1989]. The church has three naves, a raised presbytery and three doors into the north wall facing towards the tower. It is poorly built, and it is decorated with a double–beaten lime floor. The tower and the church seem to do not have direct relationship with the quadrangular tower and with the buildings that stand on the slope of the northern terrace [Piccirillo, 1989]. Although some scholars believe that the Tower had sighting purposes, acting as guard post against the dangers coming from the surrounding territories [Saller and Bagatti 1949], the most accredited hypothesis is that it has had a religious function, linked to the imprisonment of a monk or a stylite, according to a singular form of Christian asceticism derived from Syria [Wilson, 1889; Piccirillo, 1989].

The Stylite Tower has been the subject of research conducted between 1986 and 2007 by the Franciscan Archaeological Institute of Mount Nebo under the patronage of the Department of Antiquities of the Hashemite Kingdom of Jordan.

From 2013, the Institute for Technologies Applied to Cultural Heritage of the Italian National Research Council has developed a project with the aim of obtaining a detailed documentation and a systematic mapping of the structure in order to constitute the basis

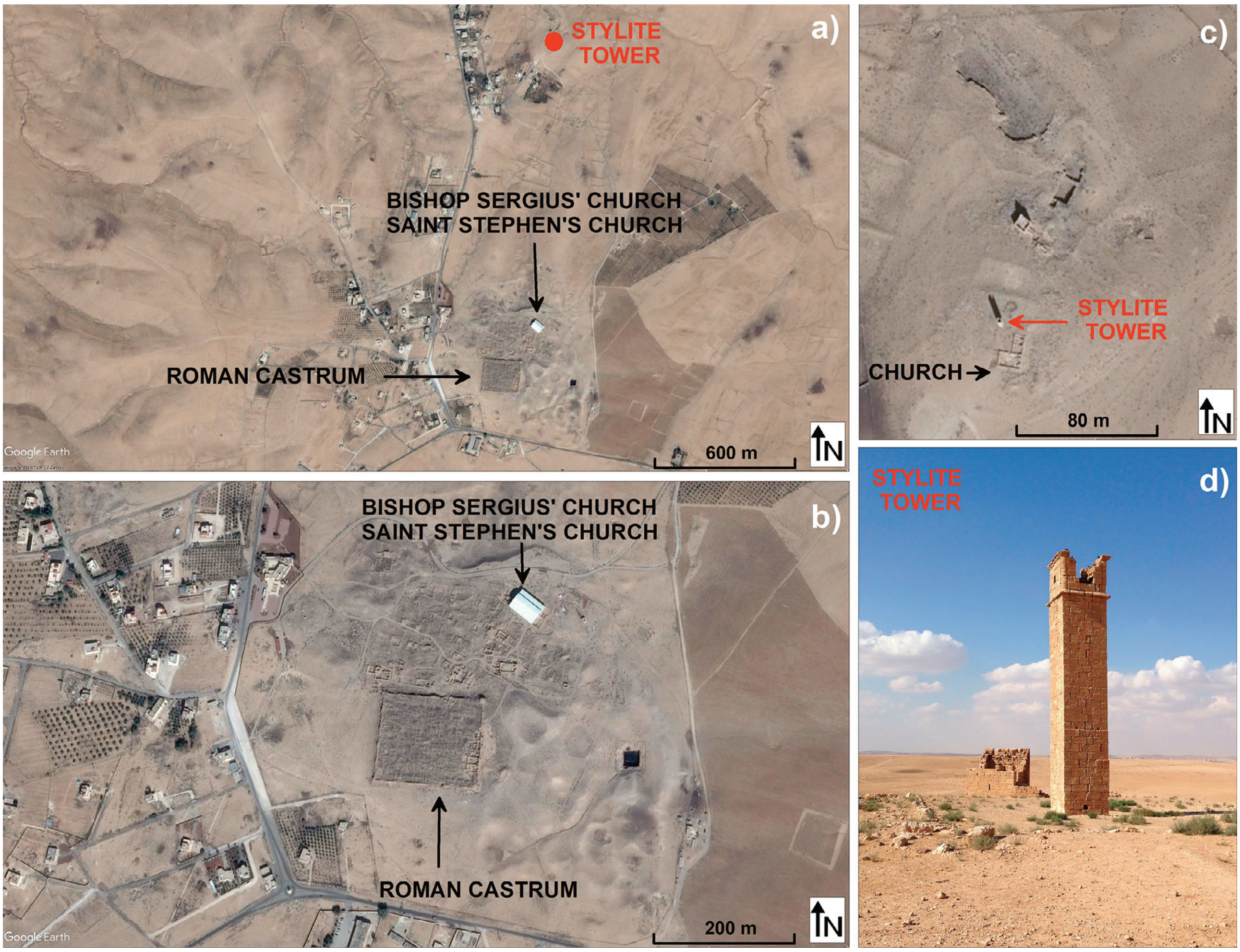


FIGURE 2. The UNESCO archaeological site of Umm ar–Rasas (Jordan): the whole site (a), the roman castrum and the byzantine churches (b) and the Stylite Tower (c, d) on the satellite image ©2018 CNES/airbus from Google Earth™.

for any further conservation and restoration interventions. Nowadays the monument shows surfaces' decay related to weathering and structural problems. The most dangerous degradation pathologies are detachments of plaster, water infiltration, erosion and fractures. Moreover, the top of the tower, probably a groin vault, is collapsed and the structure seems to be rotated and inclined respect to the original axis.

Generally, there is the lack of an organic and complete reading of the state of health of the monument and a concrete need to acquire new information, which have never been obtained to date. For this purpose, a multidisciplinary approach has been adopted complying the following workflow:

1) creation of a high–resolution 3D model of the exterior of the tower through the use and integration of laser scanning and photogrammetric methods in order to highlight the decay, even the type which is not perceivable by direct sight;
2) accurate evaluation of the technical and design choices in the project of the tower;
3) production of vertical and horizontal sections extracted from the 3D model for the evaluation of morphological anomalies of the main body;
4) construction of a Digital Elevation Model (DEM) of the floor of the tower overlapped on the 3D model through the use and integration of high–resolution laser scanning aimed at the evaluation of probable relationships between the terrain morphology and the distortions of the tower;
5) analysis of the volumes of soil flanking the tower trough the implementation of Ground Penetrating Radar (GPR) surveys with the purpose of detecting anomalies possibly indicating ancient structures or cavities below the ground;
6) production of a detailed documentation useful to plan the following restoration and reinforcement actions.

2. METHODS AND DATA PROCESSING

2.1 LASER SCANNING AND PHOTOGRAMMETRY

The three–dimensional laser scanner is able to detect, in a short time interval and with a millimetre accuracy, the spatial position of hundreds of thousands of points by elaborating point clouds. In this work, a FARO Focus 3D CAM2–X330 laser scanner has been used setting up a maximum scan range of about 330 m and a precision of ±2 mm. The density of points chosen for the single scan secured about 1 point every 4 mm to 10 meters of distance (space separating the hypothetical surface from the laser emitter). After carefully analysing the monument, the correct laser scanner positions have been determined by trying to minimize the shadowed areas and therefore obtaining the correct spacing of the point clouds and their exact recording. In total, 16 stations were established to ensure that at least three homologous points existed for each point cloud. The registration of the scans has been realised using a double alignment process, the first based on the automatic identification of suitable 3D high–reflectance targets (white spheres), with a 20 cm diameter, the second required the use of complex mathematical algorithms providing the refinement of the initial alignments. During the survey, the visibility of at least three spheres between two adjacent scans and the arrangement of scans with a suitable spatial distribution have been ensured for getting a good automatic alignment.

Data processing has required several steps:

1) The georeferencing of individual clouds using the Faro Scene and JRC Reconstructor softwares. Once the first software has aligned the scans through the help of the spheres, the second has proceed to the identification of at least 2000 common points to refine the alignment, resulting with an average error in the range of a millimetre.
2) The colorimetric overlays.
3) The construction of the overall model and extraction of all the elaborations required for the analytical representation of the structure (DXF plants, perspective drawings and sections for vector data, JPG images for photographic data and PLY and OBJ models for surfaces).
4) The surface editing operation.
5) The production of orthophotos and high–resolution textures by perfecting the model with photogrammetric shots [Cundari, 2012]. Data processing was realized using the Agisoft Photoscan software and has required the following procedures:

- Frame alignment through the Structure from Motion (SfM) technique [Remondino et al., 2014]. Three data sets have been generated: a discrete point cloud consisting of few thousands of points that describes the object's geometry, the camera positions at frame capture and the internal calibration parameters of the camera (focal length, three factors of radial distortion and two tangential to a main point).
- Construction of the geometry through dense cloud and mesh production (the point cloud has been transformed into a surface consisting of triangulated dots).
- Construction of the texture through the application of the photographic images to the 3D digital model (exportable in .dxf, .obj, .txt, .pdf, etc. format) and creation of ortophoto in TIFF, JPEG, PNG, etc. formats.

2.2 GROUND PENETRATING RADAR (GPR) SURVEY

To investigate the subsoil the Ground Penetrating Radar (GPR) uses electromagnetic waves that are sent in depth through an antenna placed on the surface and, when they reach a discontinuity, they are partly transmitted continuing their path through the material and partly reflected towards the surface where they are detected by a receiving antenna. The pulses received by the antenna used in reception mode arrive to a central unit that converts them into digital format and stores them in an internal memory. Reflections are generally caused by changes in the electrical properties of the soil, changes in water content or lithological variations. From the measurement of the travel times of the pulses, if the propagation velocity in the subsoil is known, the depth is estimated accurately.

During data acquisition an IDS RIS K2 Georadar, equipped with a multi–frequency TRMF antenna (600–200 MHz), was used. All radar reflections were recorded digitally in the field as 16–bit data and 512 samples per radar scan. The spacing between the close profiles at the site was 0.5 m and they were collected as shown in Figure 3. Radar reflections on each line were recorded at 25 scan s^{-1} (1 scan approximately corresponds to 0.025m).

Standard bi–dimensional radargrams relative to single transects were processed through the IdsGred (www.idsgeoradar.com) and GPR–SLICE 7.0 software [Goodman 2014]. Wobble removal, linear gain, band pass filter (low cutoff: 85 MHz; upper cutoff: 890 MHz), and background removal were applied to filter the raw GPR data files in order to remove high and low frequency

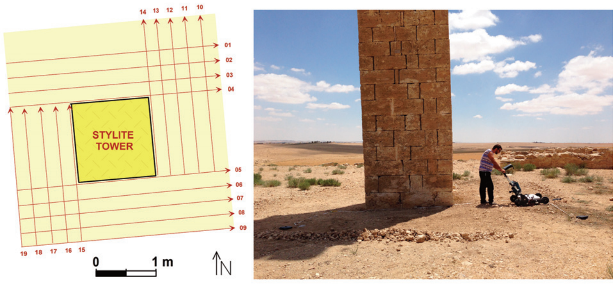


FIGURE 3. GPR survey grid (left) and data acquisition (right).

anomalies that occurred during the data acquisition, normalize the amplification and remove reflections generated by noise due to the different signal attenuation [Conyers and Goodman 1997; Goodman and Piro 2013]. A migration time domain method was finally applied to obtain a focused image of underground objects.

Thus, using the sequence of lines, a three–dimensional matrix of averaged square wave amplitudes of the return reflection was generated, and time–slices were realized for various time windows. Time slices were overlapped of 0.3 m. The creation of time slices that are at least the thickness of one or two wavelengths of the radar pulse that is sent into the ground can be useful to connect anomalies which may be at slightly different depths and as well as to see better the transitions between depths [Goodman et al., 1995]. The process involved a set of nine horizontal slices by 34 samples thick (6 ns) over a time window of 491 samples (90 ns). Data were gridded using the inverse distance algorithm, which includes a search of all data within a fixed radius of 0.75 m of the desired point to be interpolated on the grid and a smoothing factor of two. Grid cell size was set to 0.01 m to produce high resolution images.

The reflection times of the signals provide depth information [Malagodi et al., 1996; Conyers and Goodman 1997; Goodman and Nishimura 1993; Nishimura and Goodman 2000; Goodman et al., 2004a, b, 2007; Neubauer et al., 2002; Goodman and Piro 2013]. In the examined context, supposing a soil with a velocity v with which the wave spreads into the materials equal to about 0.1 m/ns, the depth h of the reflectors could be approximately derived using the equation $h = vt/2$ (where t is the time in which the electromagnetic wave fulfils the path transmitter antenna–discontinuity–receiver antenna).

3. RESULTS

The 3D metrical survey conducted until now has been a useful experiment for the integration of laser scanning and photogrammetric techniques guaranteeing the descriptive accuracy in the colors and in the details of the surveyed surface. As a result, the creation of a 3D model of the exterior of the tower made up of approximately 12 million points (1 point every 4 mm to 10 m between surfaces and emitter) has been reached. Figure 4 shows a three–dimensional view of the RGB point cloud. The 3D model has allowed the representation with great precision, in the range of a few millimeters, of the geometrical deformities of the structure. Analyzing the model, a deepened study of technical and design choices that may underlie the design of the tower has been achieved. The dimensional ratio is probably related to the Byzantine measurement system. The basis is perfectly squared, and the sides have measures between 2,52 and 2,59 m that correspond to 8 Byzantine feet [Salvatori, 2006]. Despite the top of the monument was not investigated because it is nowadays incomplete, we can hypothesize that the realization of the tower was designed using Byzantine metrical units taking into account the biblical meaning of numbers. In fact, the number 8 cannot be casual, because it symbolizes a new order of creation, the resurrection from death to eternal life.

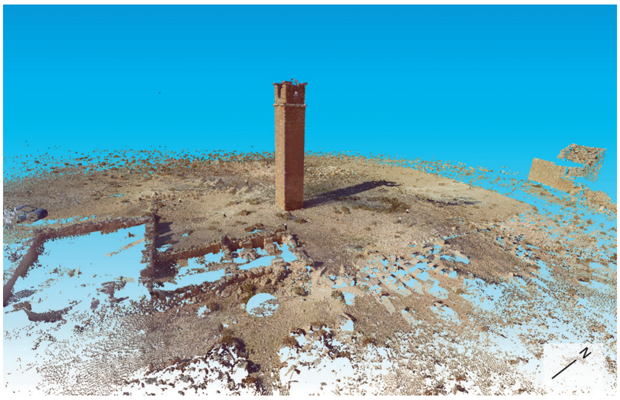
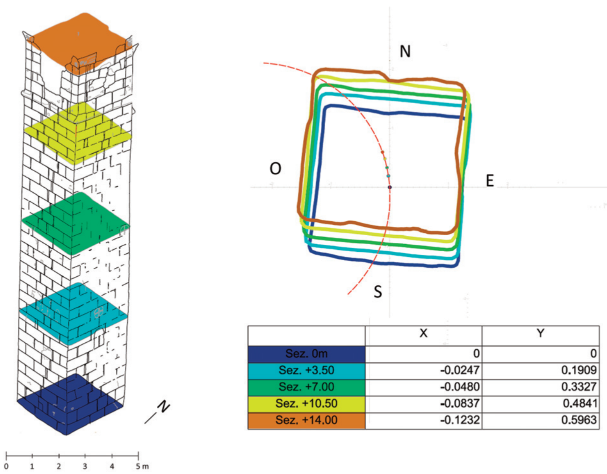


FIGURE 4. RGB visualization of the points cloud.



	X	Y
Sez. 0m	0	0
Sez. +3.50	-0.0247	0.1909
Sez. +7.00	-0.0480	0.3327
Sez. +10.50	-0.0837	0.4841
Sez. +14.00	-0.1232	0.5963

FIGURE 5. Horizontal sections of the 3D model and position of the baricentre of the sections.

The point cloud was used to extract plants and sections in .dxf format for vector data and .tiff for photographic data. Figure 5 shows an example in which the location of five horizontal sections with respect to the main body of the building, at different elevation, are reported. The drawings put in evidence that there is a deviation of the barycentre of the tower, from bottom to top, in the north–west direction and a small rotation of the upper part.

In Figure 6 a technical graphic elaboration of the four facades (North, South, East and West), the localization of the vertical sections and the profile out of plumb of the Stylite Tower (current profile, previous profile and unevenness degree angle) are displayed. The comparison between the four sections evinced that the Tower has an out of plumb angle equal to 2.28 degrees compared to an ideal vertical axis.

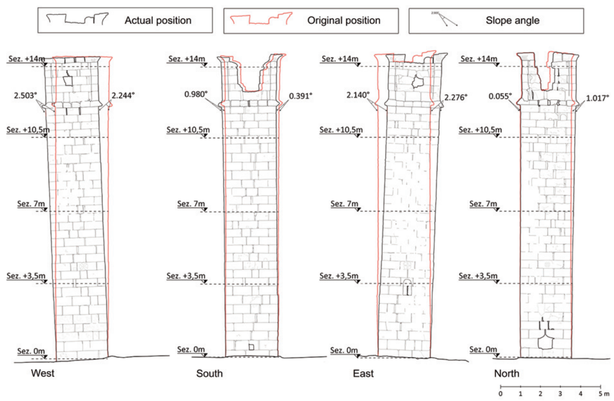


FIGURE 6. The four facades of the tower with the indication of the deviation from the original position.

Figure 7 shows the Digital Elevation Model (DEM) of the floor of the tower overlapped on the 3D model. Inside the colour scale, the red and blue colours represent respectively the highest and lower depth of the terrain floor. The DEM puts in evidence that the inclination of the tower is located where the ground has a lower depth that is in the north–west direction.

Figures 8, 9 and 10 report the main results of GPR investigation. For the sake of brevity, we show in Figure 8 seven radargrams of the whole dataset in order to give an idea of the nature of the input data used to process the depth–slices. Black dotted rectangles and letters highlight the occurrence of different shallow anomalies in the depth range 0–1.6 m. Lines 02, 05, 07 and 14 have been acquired respectively close to the northern, southern and eastern sides of the tower. They put in evidence the presence of anomalies (A, C, D in Figure 8) that can be related to coarse and compact rocks, most likely attributable to blocks used for the

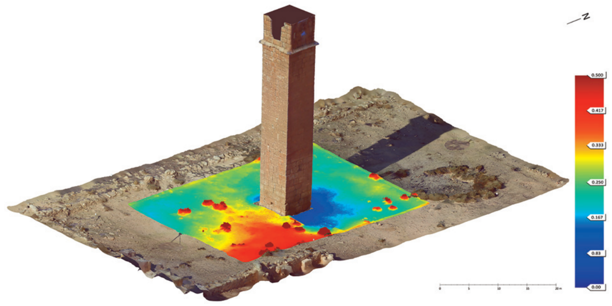


FIGURE 7. DEM of the surface around the tower.

construction of tower and the remains of structures, immersed in fine–matrix geological layers. In the western side, Lines 16 and 17 highlight two anomalies at the beginning and the end of the sections (E and F in Figure 8), while in the middle of the section in proximity of the tower there is an unexpected uniformity in materials that suggests the absence of buried structural elements in that point. Line 10, acquired in the eastern side of the grid data collection, shows a narrow anomaly (B in Figure 8) that is probably correlated to the presence of a compact stone in the ground.

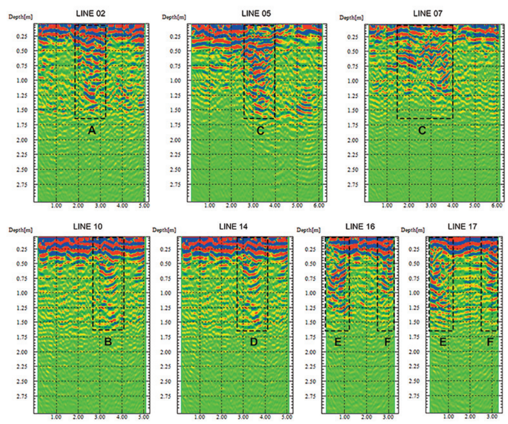


FIGURE 8. Indication of anomalies on selected radargrams from the entire data set.

All anomalies are better evidenced in Figure 9 where the horizontal slices, overlapped on the map of the Stylite Tower, are displayed in the range 0.1–1.6 m in depth. The anomalies seen in these representations depict the spatial distribution of the amplitudes of the reflections at specific depths within the grid. Within the slice, low amplitude variations express small reflections from the subsurface and therefore indicate the presence of fairly homogeneous materials. High amplitudes denote significant discontinuities in the ground and show the presence of probable buried objects or compact stones. The results demonstrate that, starting from the most superficial layers near the

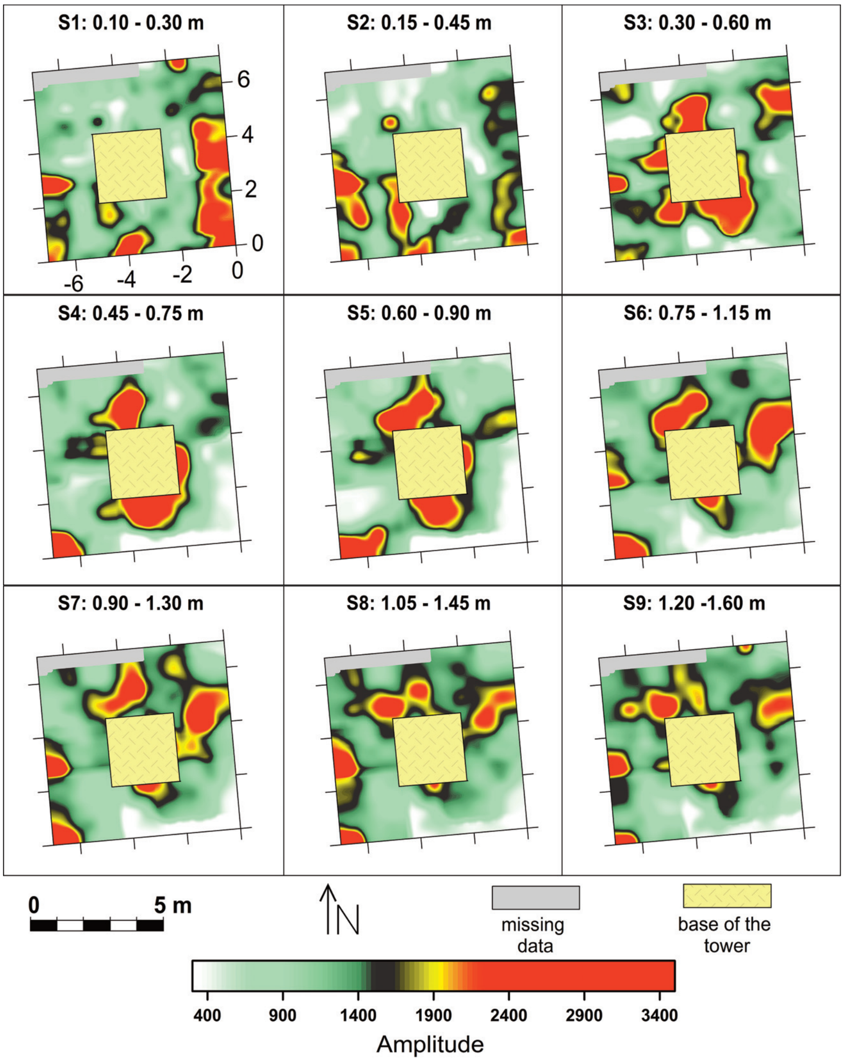


FIGURE 9. GPR depth–slices.

north–western side of the tower, only low amplitude anomalies are highlighted that are attributed to the presence of fine–matrix geological layers. Elsewhere, high amplitude anomalies indicate the presence of coarse and compact rocks. In particular, the slices related to the depth window 0–0.45 m show the presence, around the tower only of anomalies with low amplitude values. More in depth, on the southern, eastern and northern sides of the structure, anomalies with a high amplitude that is persistent throughout the investigated depth appear substantially. In any case, in the volumes of soil flanking the west side of the tower, the presence of homogeneous material emerges everywhere. For instance, this is clear in Figure 10 where the A–F anomalies discussed analysing the radargrams are reported. The absence of buried structural elements in the western side of the tower could have contributed to its inclination together in addition to other aspects such as the presence of topographical deformations, the natural structural decaying and the seismic stress occurred over the time.

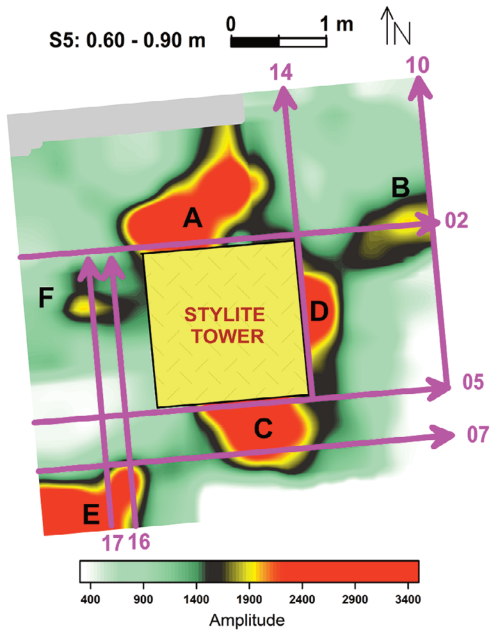


FIGURE 10. GPR slice relative to the depth range 0.60–0.90 m with indication of anomalies discussed analysing the radargrams in figure 8.

4. CONCLUSIONS

The combined use of 3D metric surveys and non–invasive geophysical surveys has enabled to acquire new information regarding the state of health of the Stylite Tower, which have never been obtained to date. The main results regard:

1) The production of a high detail 3D model faithful to the original monument from which data regarding the technical and building choices in the design, the decay of the surfaces and the morphological anomalies of the main body have been extracted. An advanced crack pattern of the surfaces, an inclination of approximately 2.28 degrees and a rotation of the main body from the bottom to the top in the north–western direction represent the most critical results of the analysis.
2) The realization of a Digital Elevation Model (DEM) of the floor of the tower that has enhanced a possible relationship between the topographic heterogeneity around the base and the distortions of the tower. In detail, the inclination of the tower is located where the ground has a lower depth that is in the north–west direction.
3) The GPR analysis of soil flanking the tower that proved the presence of a heterogeneous soil at the base of the tower with alternating fine–matrix geological layers and medium–sized rocks. In particular, the absence of buried structural elements in the western side of the tower is a substantial gathered information that can be added to all others natural factors contributed to building's movements.

The whole analysis put in evidence that the monument is in a precarious state that raises many concerns both for the conservation of the building itself and for the safety of the many tourists who visit the archaeological site.

An in–situ experimental campaign is proposed in order to understand if the consolidation works carried out in the past few years have been sufficient to stop the on–going processes. This campaign will be devoted to measure the tower's environmental vibrations and to monitor the cracks. Then, it will be possible to develop an accurate structural model to evaluate the residual resistance of the tower and design an effective retrofitting intervention for preserving it from the local and global mechanisms collapse integrating the results of this work with others in progress [Clemente et. al., 2018].

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