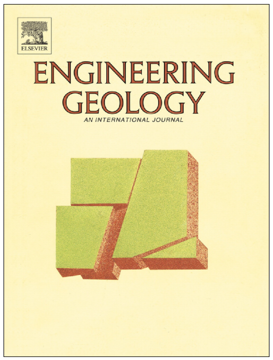

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PII: S0013-7952(18)31460-1
DOI: https://doi.org/10.1016/j.enggeo.2019.05.010
Reference: ENGEO 5133

To appear in: *Engineering Geology*

Received date: 24 August 2018
Revised date: 6 May 2019
Accepted date: 7 May 2019

Please cite this article as: E. Rizzo, L. Capozzoli, G. De Martino, et al., Urban geophysical approach to characterize the subsoil of the main square in San Benedetto del Tronto town (Italy), Engineering Geology, https://doi.org/10.1016/j.enggeo.2019.05.010

Urban Geophysical approach to characterize the subsoil of the main square in San Benedetto del Tronto town (Italy)

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ABSTRACT

Most historic urban areas have a lack of information regarding subsoil and buried structures (such as old utilities, private cellars, etc.). Therefore, when planning new engineering interventions, limited information of subsoil composition leads to greater risk when conserving and reclassifying historic urban areas. Obtaining information about potential sources of risk for infrastructures is important for civil engineering. However, only high-resolution information improves the management of important activities involving historic urban infrastructure. Although the use of direct measurements can alleviate a lack of information concerning the subsoil, the used method is, generally, expensive, invasive and interferes with everyday use of the site for long periods. Therefore, the use of low or non-invasive technologies to quickly and accurately analyse the subsoil is preferable and strongly recommended. For this purpose, a new discipline, recently termed Urban-Geophysics, is developing rapidly. This paper describes an application of Urban-Geophysics in a historically important Italian town. In order to characterize the subsoil and identify the presence of natural voids and unknown anthropic underground structures such as cellars, an extensive geophysical investigation based on use of Electrical Resistivity Tomography and Ground Penetrating Radar to perform a survey in the town of San Benedetto del Tronto (Marche region, Italy) with a total time frame of around two days. Previously unknown buried structures and geological discontinuities were able to be highlighted by using these geophysical techniques. In order to support and confirm the interpretation of the geophysical data, some geotechnical drillings were carried out. Finally, direct data validated and supported the non-invasive geophysical results. The combined results have provided valuable information to the local authorities and engineers involved in the decision-making process for the construction of new underground structures.

Keywords:
Urban Geophysics; ERT; GPR

1. INTRODUCTION

The presence of historical areas in old cities provides valuable cultural heritage that is of great interest to many people. These areas are also very attractive for tourism. However, modern life sometimes requires invasive engineering works even in these areas. For this reason, there is a strong need to obtain information about these sites, in particular with regard to old infrastructures and foundation subsoil. Contexts characterized by the simultaneous presence of ancient construction and modern underground structures is typical in several cities in the world, and particularly in Italy. Furthermore, the geological complexity of the Italian territory increases the degree of uncertainty for the characterization of the subsoil. To overcome these problems, expensive and invasive direct analyses are often carried out. The urban geophysical approach aims to provide several types of information on the urban subsoil as well as saving money and time. Moreover, it represents a reliable method of avoiding potential geological and anthropogenic hazards (Lapenna, 2017). Enthusiasm for this innovative approach based on the use of geoelectrical, electromagnetic and seismic methods has been growing fast in the last years (Miller, 2013; Gabas et al., 2014). Indeed, Urban Geophysics (UG) often represents the only way to characterize the subsoil that ensures high levels of detail in the obtainable information without interfering significantly with the life of the investigated area. Unfortunately, only some geophysical techniques are able to be used in urban areas due to strong noise resulting in a low signal-to-noise ratio. For example, metallic structures (e.g. fences, road signs, etc.) or highly insulating layers (e.g. asphalt) limit the use of electromagnetic and magnetic methods. However, there are some geophysical techniques for studying urban areas, including Electrical Resistivity and Ground Penetrating Radar methods, which often offer a good compromise in terms of resolution and depth of investigation thanks to their ability to reduce or even ignore urban noise effects.

This paper presents the results of Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) methods applied to an old town square in San Benedetto del Tronto (Marche region, Italy) in order to characterize the subsoil and detect unknown structures.

2. THE SITE OF SACCONI SQUARE

Piazza Giuseppe Sacconi (Sacconi Square) is the most important historic site in the town of San Benedetto del Tronto. It is dominated by the presence on the north side of a monumental tower (Torre dei Gualtieri or Mastio della Rocca) that was built at the end of the XV century by the Gualtieri’s family following the construction of the town’s castle. The 20m tall hexagonal tower was realized in brick masonry and is the town’s most characteristic historic building. On the west side of the tower, there is the Seminary, formerly known as Palazzo Anelli, built in 1730 and subsequently restored after being partially destroyed by air raids during World War II. The monumental Abbey of San Benedetto Martyr, realized during the XI century and modified in the XVIII century, occupies the west side of the square. This building was in the original town centre, from which the current city developed and its importance is due to it containing the remains of the patron saint. The east side of the square is occupied by Husson House, an historic civic building probably completed in the XVIII century and extended in the first few years of the last century; man-made caves located at the heart of the building have been used in the past as cellars or stores (Liburdi, 1950). Some of these underground structures are accessible, but with limited information, there is a high probability that others exist (San Benedetto del Tronto, Wikipedia web site).

From a geological point of view, the investigated area consists of sand and sandy silt layers with gravel lenses on blue-grey clay deposits at a depth of around 20-25m deep. Road ballast created from very coarse materials (including some decimetres thick layer of gravel) and 1-1.5m deep ancient anthropic soil covers the shallower buried portion. In the recent past, the square has suffered from several collapses in the surface but the cause of the subsidence was never fully investigated. In addition, wine cellars were common in the past, but their location is often unknown because they are part of old private houses.

An interest in the historical significance of the square has made it necessary to improve the level of knowledge of the presence of underground structures and to identify unknown or collapsed caves, and geophysical activities were therefore carried out. Electrical Resistivity Tomography and Ground Penetrating Radar surveys were performed to investigate below Sacconi Square, in order to provide community authorities with subsoil information to facilitate future project planning (fig.1). Three different targets were pursued: i) localization of underground utilities; ii) identification of unknown anthropic structures and archaeological features; iii) characterization of the subsoil and identification of voids and collapses.

3. URBAN GEOPHYSICAL METHODS

In order to characterize the subsoil below Sacconi Square, a geophysical field trip based on the joint use of GPR and ERT was undertaken. In this section of the paper, the two techniques are described with particular attention to their application in the urban context. ERT is based on Ohm's Law and is carried out by introducing current (I) into the ground using a pair of electrodes (commonly labelled A and B) and measuring the drop of potential (ΔV) between a second pair of electrodes (M and N). Generally, a switched square wave is the current waveform used (Binley and Kemna, 2005). This process is repeated several hundred (or even thousand) times by changing the configuration between the injection and potential electrode arrays. In a homogeneous ground, the current flows radially out from the current source and the resulting equipotential surfaces run perpendicular to the current flow lines to form hemi-spheres. In other cases, the current flow and equipotential lines are distributed in complex forms depending on resistivity values of the ground. The data acquired are expressed in the form of apparent resistivity. The obtained apparent resistivity and depth values are then processed using inversion software to calculate the 'best' set of resistivity values, to satisfy both the measured dataset and some *a priori* constraints, as well as to stabilize the inversion and constrain the final image (deGroot-Hedlin and Constable; 1990). Geoelectrical investigations are successfully employed for subsurface void detection (Zhou et al. 2011, Guerin et al. 2009, Chamon and Dobereiner,1988), for monitoring geological hazards (Kaufmann 2014, Lapenna et al., 2005, Giampaolo et al., 2016, Maillet et al., 2005, Gomez-Ortiz and Crespo 2012, Zini et al., 2014, Samyn et al., 2014), and to identify the presence of archaeological features outside and inside urban contexts (Rizzo et al., 2005; Chianese et al., 2010; Bianchi–Fasani et al. 2013; Capozzoli et al. 2017).

The other commonly-used geophysical technique for the investigation of urban areas is GPR an active electromagnetic (EM) method based on the introduction of an EM field into the ground and the subsequent study of the scattered phenomena resulting from the EM waves propagating in the subsoil. GPR is founded on Maxwell's equations, the parameter generally investigated being the velocity (v) of the EM waves related to the physical characteristics of the analysed medium according to the equation:

$$v = c/\sqrt{e_r}$$

where c is the velocity of an electromagnetic pulse in the air (0.2998 mns^{-1}) and e_r is the dielectric permittivity of the medium. The presence of lowly dispersive materials (e.g. ice, voids, salt) allows great depths of investigation while the presence of clay or water, which increases the attenuation phenomena, greatly reduces the effectiveness of the method, limiting the investigation depth to a few decimetres. GPR is one of the highest resolution geophysical methods, the resolution being relative to both the frequency of the adopted antenna and the type of the system used for the acquisition (single antenna or array of antennas).

GPR method has been successfully applied during the last three decades. It was used to localize natural and anthropic cavities and voids in the subsoil (Bottari et al., 2017); to characterize karst areas and sinkhole phenomena (Pueyo-Anchuela et al., 2010; Fabregat et al., 2017); to identify collapsing areas in urban zones (Carbonel et al., 2015; Sevil et al., 2017; Jeng and Chen, 2012); and to localize anomalies related to the presence of underground utilities (Saracin, 2017; Sagnard et al., 2016; Capozzoli and Rizzo, 2017) or archaeological buried structures (Capozzoli et al., 2015; Masini et al. 2018, Ludeno et al., 2018).

The non-invasive or less invasive methods described above were carried out under Sacconi Square to detect previously unknown underground voids, such as anthropic tunnels or cellars, and to identify any geological structures (fig.1).

3.1 DATA ACQUISITIONS

ERT data were acquired using the ABEM SAS 1000 resistivity meter. The acquisition was made by a multichannel system with 64 electrodes adopting four distinct suitably connected 16-pole cables (fig. 2) powered by an external 24V battery. A dense grid composed of seventeen parallel lines placed at 1.5m intervals was carried out. The length of each survey line varied from 25m to 53m due to the presence of obstacles or structures on the square. In order to improve the signal-to-noise ratio caused by high resistance contact between the electrodes and urban floor, the electrode holes were filled with a conductive solution (bentonite and salt). Figure 3 shows the location of all profiles; their distribution was adapted to take account of the irregular geometry of the Sacconi Square. The electrode spacing was set to 1m in order to obtain an adequate resolution for the investigated targets, whilst the expected investigation depth was approximately 9m. Along each line, two different configurations were used (Wenner and Dipole-Dipole arrays). Regrettably, the Dipole-Dipole approach provided a lower signal-to-noise ratio. For this reason, only the data acquired with the Wenner array were suitable for processing. Figure 4 shows the 3D distribution of the acquired data (electrical apparent resistivity data) in which it is possible to observe an electrical resistivity range between 10 to 2000 Ohm.m. Before the inversion procedure, all the acquired data were processed to take into account spikes and corrupted values.

Simultaneously, GPR surveys were performed with a GSSI SIR-3000 System coupled to a 400 MHz antenna and survey wheel. The GPR surveys were carried out in two main steps according to the scheme plotted in figure 3. The first 52 parallel profiles were acquired in the same direction as the ERT's lines with an interval distance of 0.75 m, retracing alternate lines investigated with ERT. Subsequently, 28 profiles were carried out at an angle of 60° to the first, between San Benedetto Abbey and Husson House, to increase the resolution of the results in the proximity of a known cellar.

3.2 DATA PROCESSING

The ERTlab64 software (http://www.ertlab64.com/) was used to invert the resistivity data. The software, based on a tetrahedral finite element method of inversion, allows a full three-dimensional topographical electrical model to be created. The inversion code was implemented on all the acquired results along each profile in order to have around 5000 items of data. The mesh was built taking into account a dimension grid of about 1m in the X and Y directions and 0.5m along the Z depth. Figure 4 highlights the dense coverage of the mesh used to characterize the subsoil while the coloured dots represent the distribution of the apparent resistivity data. Several hundreds of thousands of cells were therefore used to build the mesh. The 3D inversion parameters combined the robust algorithm with a data error reweight and the boundary condition incorporated both Neumann and Dirichlet approaches. The 3D inversion process took a long time even with a high-performance personal computer (around 4 hours for each inversion).

The GPR data were elaborated with basic operations in order to safeguard the quality of the data and to avoid the recording of non-existent artefacts. The first step consisted of editing and georeferencing the acquired data, assigning the correct coordinate of each radargram. The start time of each acquisition was corrected to the main bang removing information of no value contained in the radargram. A background removal filter was applied to remove any noise affecting the data. The measured signal was amplified using a linear function of gain in order to compensate the intrinsic attenuation of the EM signal and a band-pass frequency filter was implemented to reduce any noise increased by the gain function previously adopted. The data were migrated with the use of the Kirchhoff algorithm based on an estimated EM waves velocity equal to 0.09 mns^{-1}, obtained analysing the diffraction hyperbolas generated by the existing underground utilities. Finally, the time window of the dataset was limited to remove the noisiest part of the radargrams. Once the 2D data was processed, a 3D representation of the investigated site was created using the Reflex-W software (Sandmeier, 2013). Further, regarding the square used to enhance alignments measured perpendicularly with respect to the direction of acquisition, three distinct 3D volumes were created. The first was built using only the radargrams acquired in parallel to the ERTs, the second was realized with the radargrams acquired with an inclination of about 60° in relation to the first readings, and the last model was created using all the radargrams of the dataset. Results achieved with this strategy, based on different modes of interpolating the reflection amplitudes due to the variation of the EM impedance within subsoil, demonstrate a simplification in the process of detecting alignments associated with underground utilities or other structures.

4. RESULTS AND DISCUSSION

In order to define the 3D electrical resistivity images from misfit data with an $R^2 = 0.93$ (the linear relationship between apparent and calculated resistivity value), several inversion processes were made. The figure 5 shows the 3D electrical resistivity image obtained by Voxler software (Geotomo software) taking into account the distribution of the final electrical resistivity model created with the inversion software. The electrical resistivity range measured was between 5 to 1500 Ohm.m. The 3D resistivity model highlights four main electrical resistivity layers. The near surface electrical resistivity layer at a depth of about 1.0-1.5m is characterized by relatively high resistivity values (>300 Ohm.m). The second, with a variable thickness between 1 and 2m, has a very low resistivity distribution (< 40 Ohm.m) and below this it is possible to observe some relatively high resistivity lenses (>100 Ohm.m) at a depth ranging between 2.5 and 6m. The deeper zone is characterized by low electrical resistivity value (< 50Ohm.m). If we compare the geophysical results with the geological stratigraphy, the shallow, relatively high resistivity zone can be associated with the anthropic stratigraphic layer composed of coarser materials. The shallow and deep relatively conductive electrical layers can be associated with sand and sandy-silt. In contrast, the deep relatively high resistivity zone could be associated with a large gravel lens or an empty or stocked wine cellar.

In order to identify anomalies related to the presence of buried surface structures, considering the antenna directivity of the GPR system (Annan 1973, Annan et al. 1975), several slices from a 3D GPR dataset have been highlighted (fig. 6). These contain several alignments and geometries associated to old buried structures. The figure 7 was produced to show some of these reflective features in relation to the existing buildings. At an estimated depth of about 1.15 m, different alignments due to the presence of underground utilities were identified (black dashed lines in figure 7). Amongst these, only the ones located below the square floor were known. At the same depth, a highly reflective area that hides a potential archaeological structure, possibly collapsed parts of the existing cellar of Husson House, was identified between the tower and the Abbey (areas delimited with blue dashed line in figure 7). Other reflections broken in continuity could be associated with the presence of anthropic material used for levelling the natural soil. Likewise, the chaotic reflections measured at a depth of about 2.25m are due to coarser, geological gravel and pebbles, confirmed by direct measurements. In addition, it is worth noting an area characterized by high amplitude reflections placed between the east side of the Gualtieri tower and the west side of Husson House that could be associated with the presence of archaeological structures or to the partially-explored cellar of Husson House.

Finally, GPR data were used to integrate the 3D model obtained with resistivity measurements. Figure 8 shows the 3D ERT model combined with the GPR slice theoretically placed at a depth of 2m. The co-rendered image is defined as a simplified geophysical integration (Dell'Aversana, 2014) between different results obtained by two geophysical techniques. Therefore, even if it is an *a posteriori* qualitative comparison of models obtained separately through an independent process, the approach shows significant benefits by highlighting correlations and inconsistencies between the two different results. In fact, only the ERT results show a high resistivity value distribution in the first 3m of subsoil without any clear evidence of buried surface structures. In comparison, the co-rendered image provides a useful contribution to the process of the analysis and interpretation of the models. Figure 8 highlights high resistivity zones (coloured red) where there is a high amplitude of EM signal due to reflections of buried structures. This approach becomes very useful in urban areas where the heterogeneity of the shallow subsoil is so widespread. Indeed, GPR was not able to investigate below 3m, therefore, the 3D electrical resistivity image produced (fig. 9) highlights only the relatively high resistivity zones to give an interpretation of the urban geophysical results obtained in the deeper layer (>3m).

Two large, high-resistivity zones can be observed, one a large lens placed in the south of the square, the second in the north being more geometric (L shape) and extending from the eastern building. Taking into account the shape of each high resistivity zone, the first can be associated with gravel lens whilst the L shape of the second is typical of an anthropic void (such as cellar). This interpretation was conclusively confirmed by results from geotechnical drilling survey. As part of a municipal project, several boreholes were drilled in the historic city centre, five of which were made in Sacconi Square following the urban geophysical results (see fig. 9). The S1, S3, S4, and S5 have investigated depths of between 7.50 and 10 m from the surface, while S2 was the deepest at 24m, in order to reach the bedrock (blue-grey Pleistocene clay). S2 showed the presence of a possible 1.5m-deep void (from approximately 6.50 m to 8 m). Above and below these zones, the presence of sandy-clay with some scattered gravel was detected. The S5 hole has revealed the roof of a cellar at 4m with a height of about 2m. Above and below the cellar, sandy-clay material was detected. Regarding S1 and S3, information gained from drilling has also revealed the sandy-clay geological layer, but with large gravel lens in a sandy matrix. Finally, sandy-clay layer and a small band of gravel typifies the S4 holes. Initial excavation of the surface (down to 1.5m) revealed a layer containing stones, voids and heterogeneous materials. A strong correlation with the GPR and ERT data was determined by comparing direct evidence and geophysical results. Indeed, the shallow, historic, heterogeneous materials show up clearly in the high amplitude reflections of the EM waves. The deep geoelectrical model highlights a strong relationship between high resistivity zones and anthropic voids (cellar) or gravel lens, while the low resistivity zone is justifiably associated with sandy-clay layers.

5. CONCLUSIONS

The main objective of this paper is to demonstrate the key role of applied geophysics in supporting actions for urban planning that adopt non-invasive, high-resolution techniques based on the study of geoelectrical and electromagnetic behaviour of the subsoil. The results obtained in an historic zone of the urban area of San Benedetto del Tronto (namely Sarconi Square) demonstrated how it is possible to adopt non-destructive methods in an area where the lack of information on the subsoil represents a great risk to the conservation of an area when it is subjected to invasive engineering work.

The paper highlighted how a planned geophysical approach could give important information on subsoil-content when no current direct data exists, and how this can support decisions on the positioning of boreholes.

Thanks to the acquisition of high-resolution GPR images, supported by ERT results, unknown structures placed in the square have been identified. Moreover, as expected, GPR information alone is not able to identify the presence of voids or similar anomalies distributed in the deeper part of the investigated area, estimated to be between 2.5 and 3m. For this reason, a significant contribution to the investigation of subsoil anomalies was made by ERT, demonstrating its capabilities in surveying the subsoil using a dense grid of electrodes evenly distributed on the square's floor that require a minimal amount of invasive work (only a small hole for the electrodes). Moreover, the results obtained highlight the necessity of using geoelectrical arrays with a high signal-to-noise ratio due to high urban noise caused by the high electrical resistance between the electrodes and the ground. The best results were obtained by using the Wenner method. Furthermore, this work has demonstrated how the integration of two techniques is not only useful but also sometimes clearly necessary, especially when the subsoil shows a high heterogeneity, such as that in urban areas. The integration of the results, along with a simple co-rendering image, has allowed the identification of several anomalies consistent with the presence of unknown collapsed cellars or a combination of gravel lens and sand. The results obtained also contribute to highlighting the possible risks for each type of engineering intervention carried out in the investigated area and offer a possible means for identifying the cause of localized subsidence in some areas of the square. Finally, the presented work demonstrates how Urban Geophysics could be considered the optimum tool for urban applications due to its fast and minimally-invasive approach. The work undertaken using the urban geophysical approach described in this paper required only two days of acquisitions, with minimal disruption to the use of the square and, in contrast to conventional methods, with no damage to the investigated area.

6. ACKNOWLEDGEMENTS

We wish to thank the Municipality of San Benedetto del Tronto town and all the people that help us in the field. The authors thanks the editor and the three anonymous referees for their useful comments and suggestions improving the quality of the paper. The authors thanks Tomogea srl for supporting us for the geophysical activities described in the paper. The authors are deeply grateful to Chloé Salisbury for assistance with the English version of the manuscript.

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FIGURES

Figure 1: (a) San Benedetto del Tronto (Italy); (b) the investigated square. In the square are localized the Torre dei Gualtieri on its north side (c) and other historic buildings

Figure 2: Photo of the Sacconi square during the acquisition work. (a) and (b) GPR system coupled to an antenna of 400 MHz and survey wheel; (c) Georesistivimeter ABEM SAS 1000; (d) one profile with the electrodes installed on the square floor.

Figure 3: Grid profiles on the Sacconi square. Blue lines are the ERT and GPR profiles. The magenta lines were investigated only by GPR.

Figure 4: 3D acquired data distribution. 3D view (a) and top view (b). The white areas were located buildings or obstacles.

Figure 5: 3D ERT of Sacconi Square with indications of the geotechnical drilling positions (S1-S5).

Figure 6: Depth Slices extracted every 50 cm from the 3D GPR square model.

Figure 7: GPR depth slices with identification of the most important alignments associated to underground utilities indicated with black lines (a) and potential collapsed areas of archaeological features highlighted with blue lines at the depths of 1.75 (b), 2.25 (c) and 2.75m (d). (e) The Sacconi square from Google Earth image.

Figure 8: Co-rendered image obtained by the overlapping of a GPR and ERT slices extracted by the respective 3D model at the depth of 2m

Figure 9: 3D electrical resistivity image with only the electrical resistivity values greater than 80 Ohm.m. The position of the geotechnical drillings performed in the areas are indicated (S1-S5).

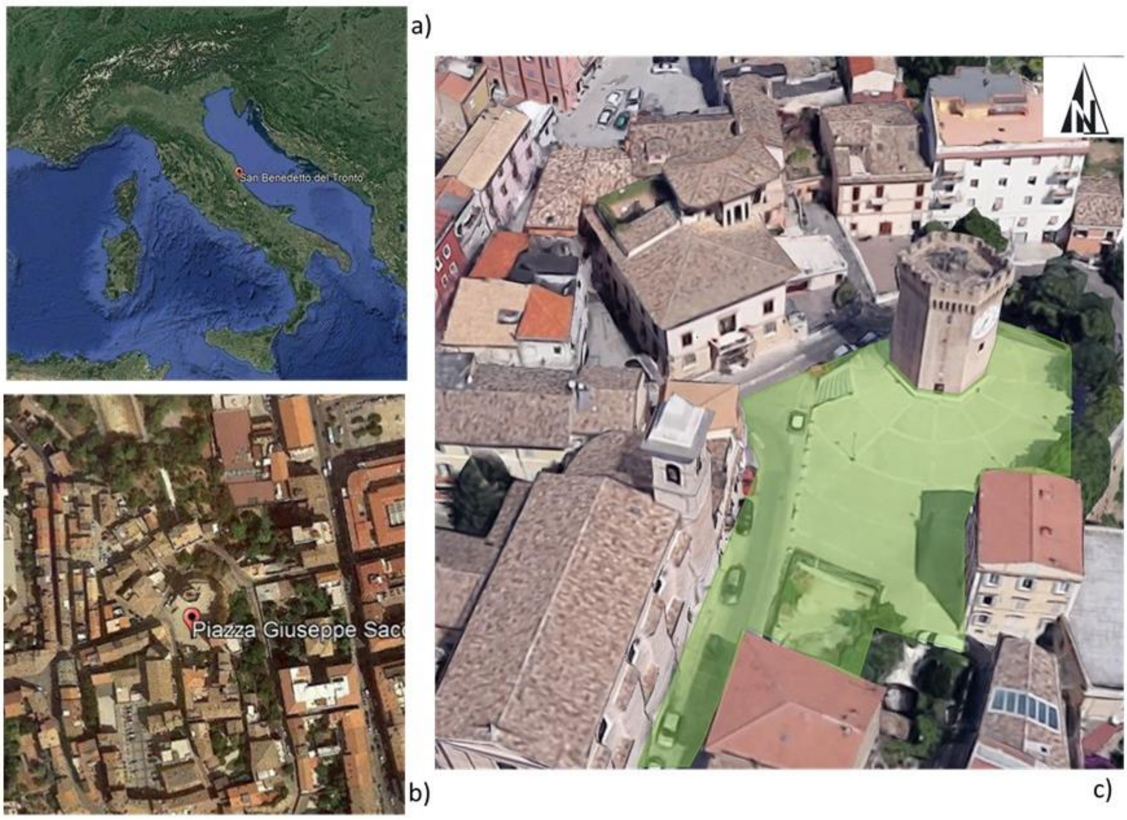

Figure 1

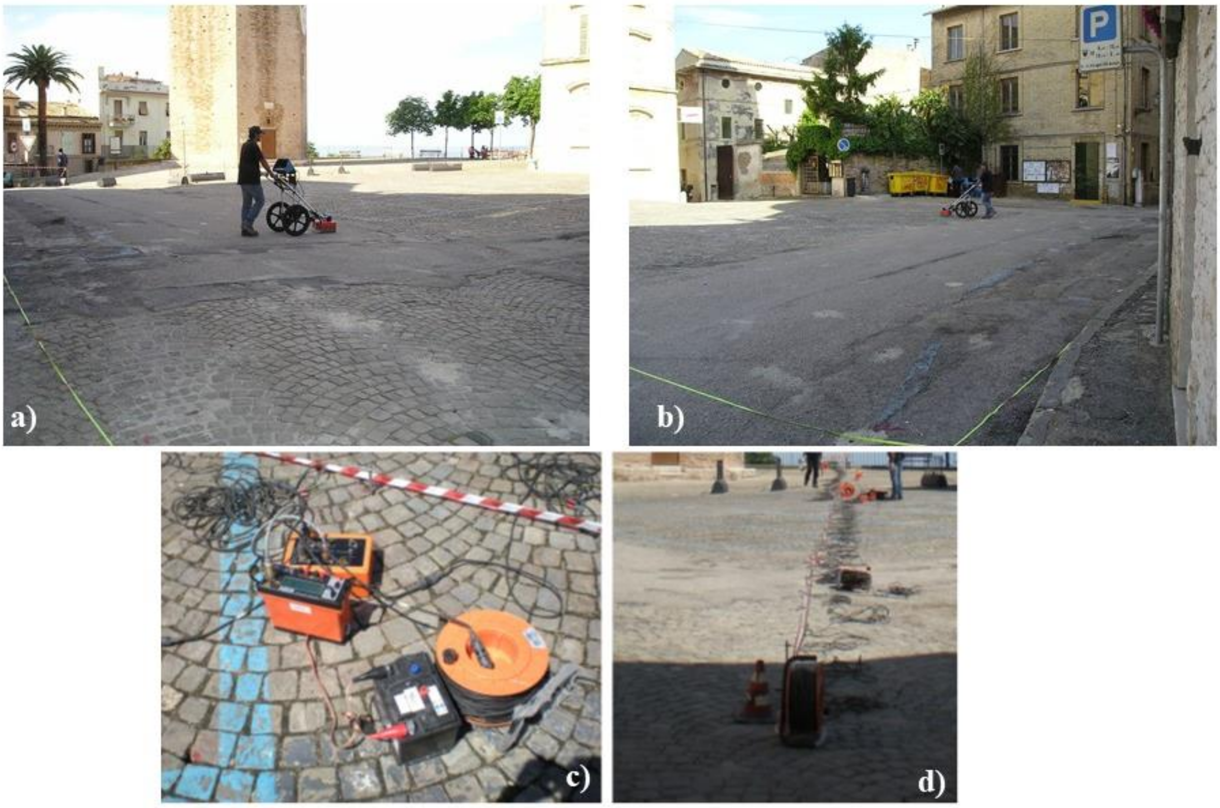

Figure 2

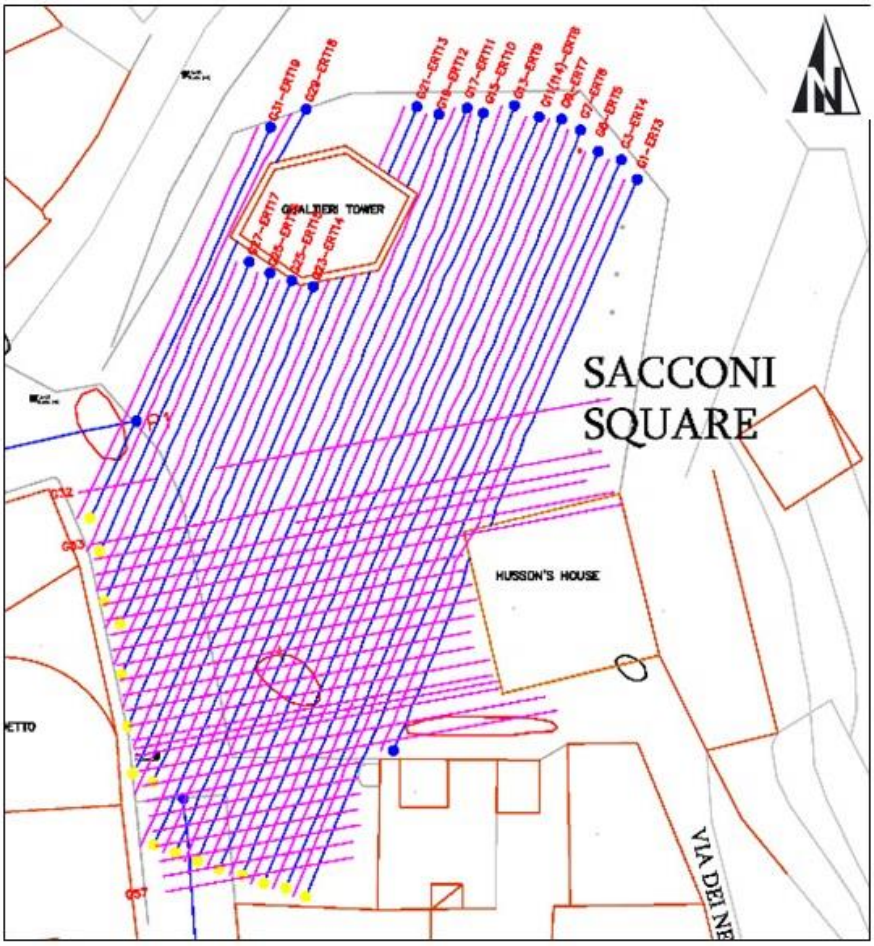
G31–ERT19
G29–ERT18
G21–ERT13
G19–ERT12
G17–ERT11
G15–ERT10
G13–ERT9
G11(14)–ERT8
G9–ERT7
G7–ERT6
G5–ERT5
G3–ERT4
G1–ERT3
GUALTIERI TOWER
G27–ERT17
G23–ERT14
N
SACCONI
SQUARE
G1
G32
G33
HUSSON'S HOUSE
ETTO
G57
VIA DEI NE

Figure 3

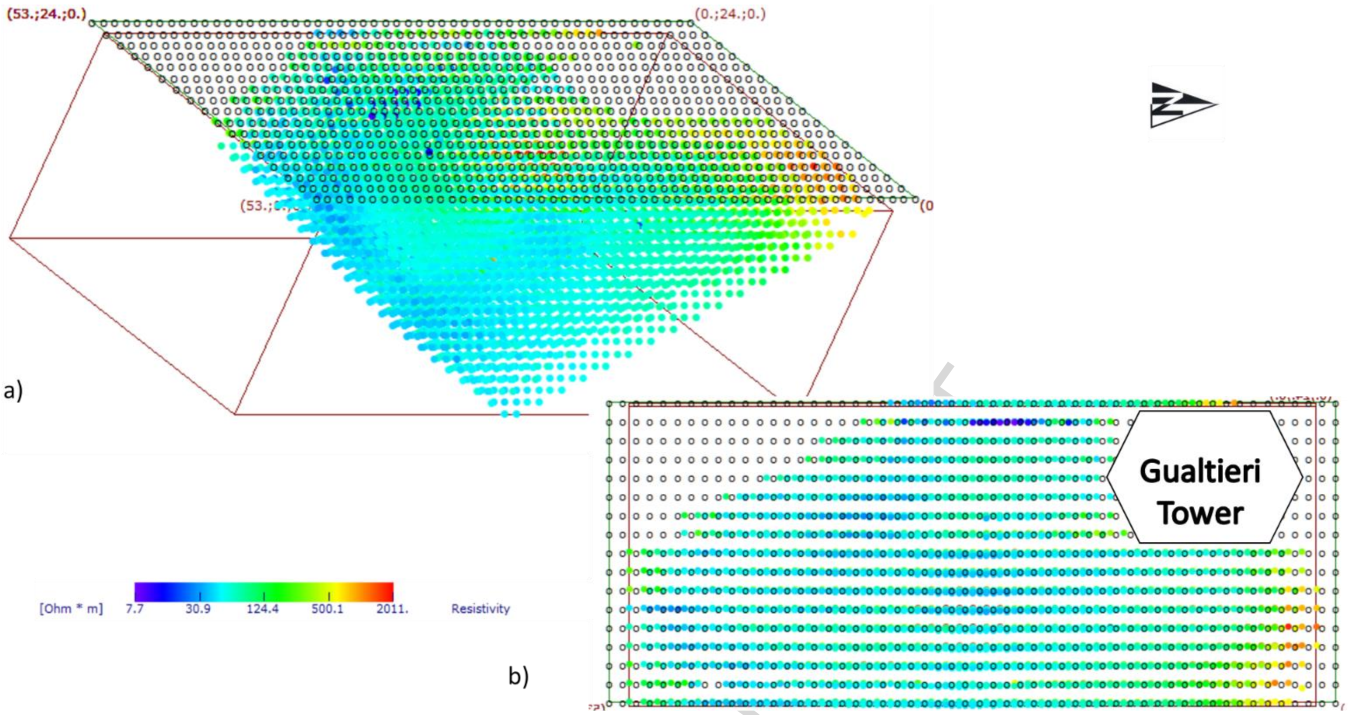
(53.;24.;0.)
(0.;24.;0.)
(53.;
(0
a)
[Ohm * m]
7.7
30.9
124.4
500.1
2011.
Resistivity
b)
Gualtieri Tower
N

Figure 4

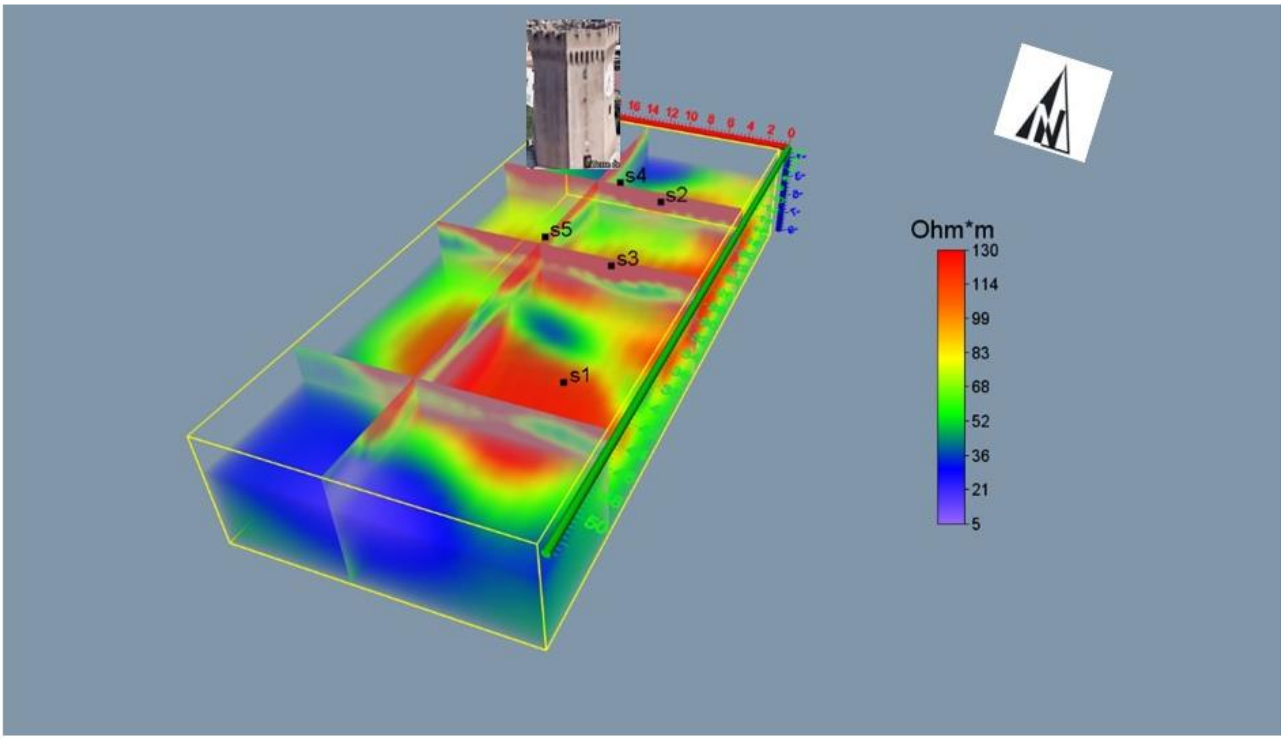

Figure 5

Depth = 0.50 m

D = 0.75 m

D = 1.00 m

D = 1.25 m

D = 1.50 m

D = 1.75 m

D = 2.00 m

D = 2.25 m

D = 2. 50 m

D = 2.75 m

Figure 6

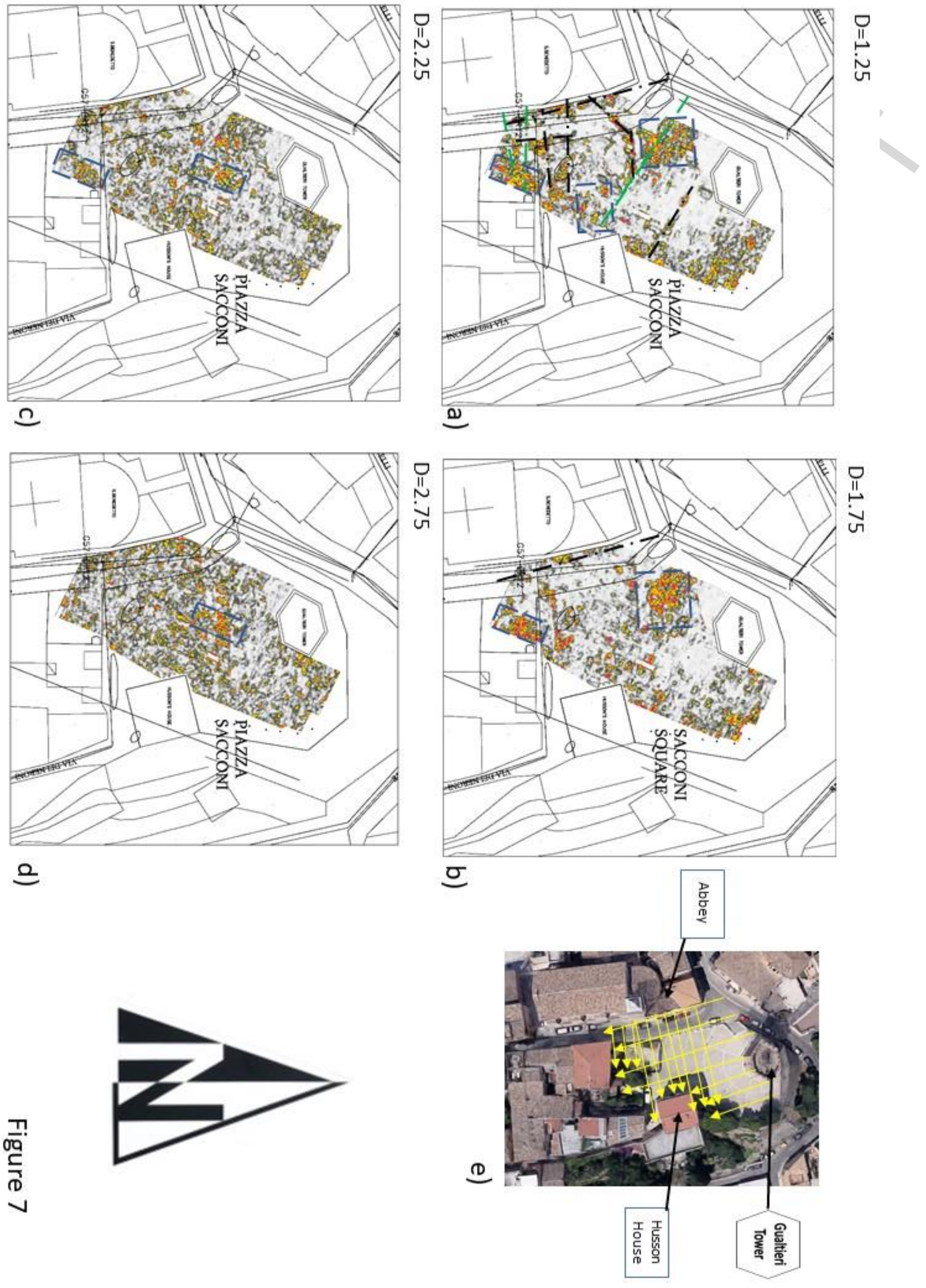
D=1.25
D=1.75
D=2.25
D=2.75
a)
b)
c)
d)
e)
PIAZZA SACCONI
SACCONI SQUARE
PIAZZA SACCONI
PIAZZA SACCONI
Abbey
Gualtieri Tower
Husson House

Figure 7

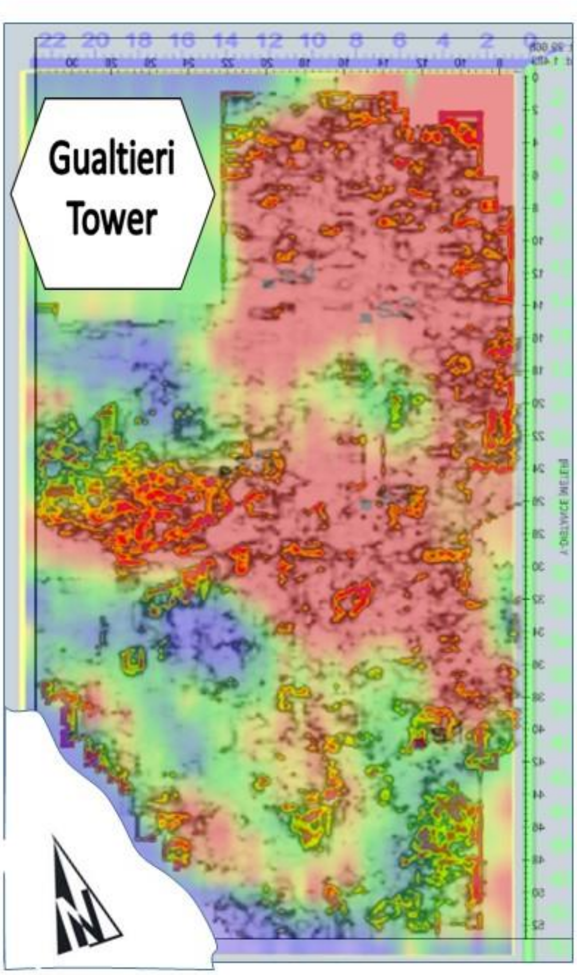

Figure 8

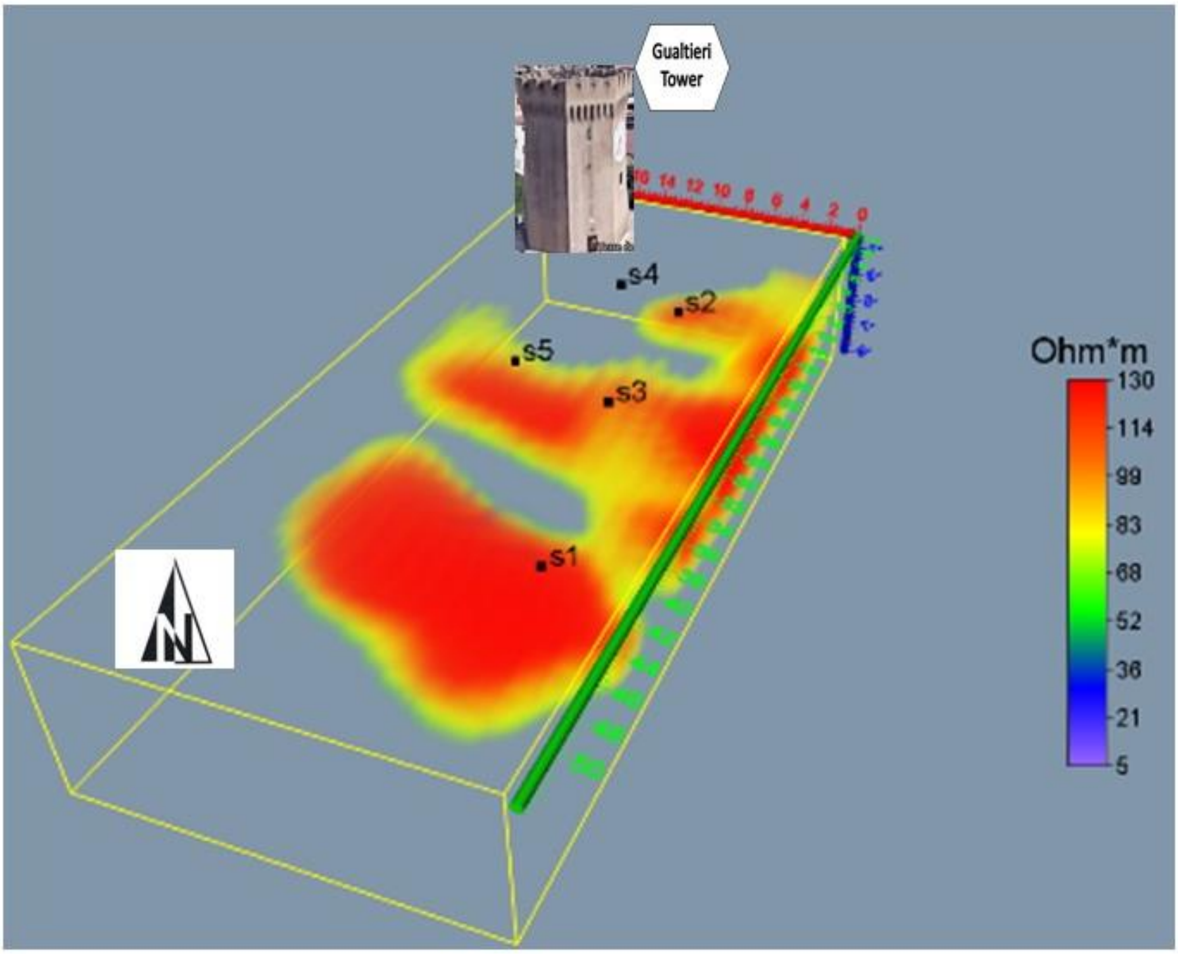
Gualtieri Tower
16 14 12 10 8 6 4 2 0
s4
s2
s5
s3
s1
N
Ohm*m
130
114
99
83
68
52
36
21
5

Figure 9

Highlights

- GPR and ERT applied in an Urban Italian historic town (San Benedetto del Tronto)
- Geophysical information have identified unknown ancient structures
- 3D GPR and ERT high resolution models
- Direct measurements have validated the geophysical data