Geophysical prospections applied to historical centres.

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Abstract: The appropriate representation of the conservation status of a Cultural Heritage constitutes a primary element of knowledge in order to guarantee the success of a project concerning its valorisation and fruition. In this context the use of non-destructive geophysical methods such as electrical tomography, georadar and electromagnetic system is a cognitive tool to be used in restoration before any enforcement action. In particular, geophysical methods have a very important role in the redevelopment of historical city centres and they are helpful in situations, for example, where areas limited by ancient walls built by the original settlers of the city are destined to the construction of public buildings and it is therefore necessary to map the territory in a predictive way. They are also useful in redevelopment and monitoring projects of historic buildings in the recovery of buried ancient structures beneath new buildings in the view of an exploitation of the original structures of the city. In this work three examples of application of non-invasive geophysical prospections in the context of rehabilitation of historic centres are proposed: Frigento (Avellino, Italy), Alife (Caserta, Italy) and Nicosia (Cyprus).

Keywords: Geophysical prospection, historical centres, redevelopment projects, monitoring of state of conservation.

Introduction

Historical centres play a very important role not only in the urban plan, but also for the monumental, artistic, historical and environmental value that they express. Their protection needs to reconcile two fundamental and different requirements: on the one hand the preservation of ancient history and, on the other hand, the urban transformation of the territory. The historical centres, heart of urban activities, have undergone many changes in the last centuries. Despite these changes, they still have a vital role in the city. They represent the key point of urban areas and reflect the economic soul and the image of the city. The historical centres are often characterized by ancient and compact constructions and very collected and connected solid buildings. Some structural elements of these buildings, such as arches and buttresses, were introduced to repair the damage caused by natural events.

In the urban planning, the historical centres are considered as areas to be revitalized, improved and regenerated, both for planning and development for socio-economic purposes. Today they are not considered as static objects or mummified tissues, but as living works which should be protected and not simply preserved. They are identified like urban organisms of ancient formation that gave rise to the modern city and urban structures that have saved traditions, processes and rules (SCOCA & D'ORSOGNA 1996). They are composed by ancient buildings, roads and urban free spaces.

In 2007, for instance, the Italian State approved a draft law concerning redevelopment and restoration of historic centres and ancient villages of Italy. The State promotes measures for protection and enhancement of historical centres, allowing to the Municipalities to identify areas of interest within the perimeter of the historical centres. It enhances public and private integrated projects for urban regeneration and the protection of architecture and Cultural Heritage. It also promotes static consolidation and anti-seismic measures for buildings. All these measures were meant to improve the collective enjoyment of Cultural Heritage.

In these projects concerning the valorisation and restoration of historical centres and restricted areas non-destructive investigations, such as remote sensing and geophysical surveys, are usually used for a prior knowledge (CAMMARANO et al. 1997, ZATROW et al. 2006, CAMPANA & PIRO 2009, COZZOLINO & DI GIOVANNI 2014). For example geophysical methods are applied in redevelopment projects of historic buildings in order to monitor their state of conservation, to analyze the construction features, to define the walls texture, to examine any incorporated architectural elements, to define features and thicknesses of decorative or structural stone facings and to recognize and characterize foundation structures. They are also used to map the territory in a predictive way in areas not yet built destined to the construction of public or private buildings. In historical centres these areas are often surrounded by the ancient walls of the city. It is therefore necessary to have a very precise and complete knowledge of the potential presence of ancient buried structures. The geophysical investigations are helpful to recover hidden constructions beneath new buildings, thorough the definition and discovery the ancient spatial planning of the city.

In this work three examples of application of non-invasive geophysical prospections in the context of a rehabilitation of historic centres are described: Frigento (Avellino, Italy), Alife (Caserta, Italy) and Nicosia (Cyprus).

Electrical resistivity tomography (ERT) and Ground penetrating Radar (GPR)

Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar are some of the most reliable prospecting tools in the field of Cultural Heritage, thanks to technological and methodological developments in recent years, which have made them fast target-oriented methods (CLARK 1996, CAMMARANO et al. 2000, GAFFNEY & GATER 2003).

ERT is based on the measure of the electrical resistivity, a physical parameter that has a large variability which allows a ready distinction of the main archaeological and architectural structures and bodies from the hosting material. The technique employs an artificial source of direct or pseudo-direct current injected into the ground through point electrodes, thus creating stationary current flow into the earth. By measuring potentials at the surface in the proximity of the current flow, it is thus possible to determine the resistivity of the subsurface for a given electrode geometry (DOBRIN & SAVIT 1988, TELFORD et al. 1990, PARASNIS 1997, REYNOLDS 1997).

The solution for the electrical potential arising from an electrical current flowing into the ground from a point source of current (a grounded electrode) is the starting theoretical point for the resistivity prospecting method. In practice, there is always a device of four electrodes used to measure the ground resistivity: two energizing electrodes are used for injecting a current and two receiving electrodes for detecting a voltage

(potential difference). Inhomogeneities, like electrically better or worse conducting bodies, are inferred from the fact that they deflect the current and distort the normal behaviour.
The potential difference can be measured for an array of known geometry and injection current. For a homogeneous isotropic subsurface, the resistivity is equal to the bulk resistivity of the half-space and hence constant for any injection current and electrode geometry.
However, as the resistivity is an intrinsic property of homogeneous material and the subsoil is generally a complex distribution of different materials with different resistivities, the key concept of apparent resistivity, is defined. In simple terms, it is a volumetric average of a heterogeneous half-space, except that the averaging is not done arithmetically but by a complex weighting function dependent on the 4-electrode device. Several electrode arrangements are used in geoelectrical prospecting. As long as the electrode arrangement is varied, a different value of the calculated resistivity for each measurement is obtained.
Thus it must be remarked that any of the apparent resistivity representations has only a rough relationship with the real resistivity pattern, whose modelling is the ultimate purpose of the survey. In fact, shape and amplitude of the anomalies, which strictly represent shifts among different apparent resistivities, depend not only on the unknown true resistivity pattern and data density, but also on contamination due to even small inhomogeneities close to electrodes. In order to remove corrupting effects and model the survey targets as accurately as possible, a numerical inversion is needed to convert apparent into real resistivities.
The ERT approach comes from taking many apparent resistivity determinations registered in as many locations as possible and involves the joint inversion of many independent tests, using an algorithm to discern subtle details from differences which would otherwise not be seen in any test. The inversion of an apparent resistivity dataset collected by the profiling field technique gives rise to a two-dimensional (2D) ERT. If one assembles a set of parallel profiles the inversion of the whole apparent resistivity dataset provides a three-dimensional (3D) ERT.
Until the availability of computers, the interpretation was based on the adjustment procedures curves. Since the direct problem for stratified media was solved by the theory of linear filters (GOSH 1971a, 1971b), many papers have appeared dealing with the automatic and numerical interpretation (INMAN 1975; KOEFOED 1979, POUS et al. 1987, ZOHDY 1989). In recent years there has been an increase in the use of two-dimensional and three-dimensional algorithms (LOKE 2004, SASAKI 2006, HA et al. 2006, PIDLISECKY et al. 2007, MARESCOT 2008, DE GROOT-HEDLIN & COSTABLE 1990). In this work the 3D probability tomography method is suggested as a tool to detect the presence of anomalies and to highlight the geometry of the buried sources (MAURIELLO & PATELLA 1999, 2009). The purpose of the technique is the design of an occurrence probability space of elementary anomaly sources, located anywhere inside an explored underground volume. In geoelectrics, the decomposition is made within a regular resistivity lattice, using the Frechet derivatives of the electric potential weighted by resistivity difference coefficients. The main features of the method are: unnecessity of a priori information; full, unconstrained adaptability to any kind of dataset, drastic reduction of computing time of even two orders of magnitude with respect to standard deterministic inversion tools, independence from data acquisition techniques and spatial regularity, capability to resolve complex continuous resistivity variation. Many field cases were dealt with using this approach (e.g. CAMMARANO et al. 2000; DI FIORE et al. 2002, ALAIA et al. 2008; COMPARE et al. 2009a; 2009b) and in all cases, the procedure proved to be a reliable tool for the most probable locations of the sources of the

measured apparent resistivity anomalies to be highlighted at the appropriate depths. No information can, however, be deducted as it regards the estimation of the real resistivities to associate with these bodies. In order to approach also this last objective, the probability-based ERT inversion (PERTI) has been proposed by Mauriello and Patella (2009). The purpose was to combine the high geometrical resolution power of the probability tomography imaging with the need of reconstructing the most probable real resistivity pattern (COZZOLINO et al 2012, 2013).

In recent years the use of Ground Penetrating Radar (GPR) techniques for archaeological prospecting has assumed increasing diffusion mainly due to the fast execution times, the non-destructive investigation and easy interpretability of results (GOODMAN 1994, BUTLER et al. 1994; STERNBERG & MCGILL 1995; TYSON 1994). The GPR is based on electromagnetic waves reflection, physical properties of conductivity and permittivity and magnetic permeability of bodies: an electromagnetic wave is transmitted down through a transmitting antenna, it is reflected by buried interfaces and received back to the surface by the receiving antenna. During GPR surveys two different quantities are measured: the two-way-time that is the time required by electromagnetic wave to get from the transmitter to the discontinuity surface and back to the surface, and the amplitude of the reflected wave. The two-way-time depends on the speed of the electromagnetic wave through the material and provides information on the depth to of reflectors. The amplitude, that is the energy quantity that comes back to the surface after the reflection, depends on the energy of the wave sent into the ground, the quantity dissipated along the way and the difference between electromagnetic properties of materials that determine the reflection surface. In order to identify an object, it is necessary that the wavelength is comparable to its size and can thus generate a reflection (DAVIS & ANNAN 1989). For example, if the object to be detected is a layer of sediment, identifying the upper and lower discontinuity, the layer thickness must be at least equal to the wavelength of the signal that is being used. For this reason, the smaller the objects are, the higher the frequency of the antenna is required.

In the GPR survey vertical sections are produced through which it is possible to locate objects or discontinuity surfaces buried in the subsoil. This is possible because wave reflections are generated during regular time intervals: generally the horizontal resolution achieved in radar profile is better if the range is smaller. All recorded tracks are displayed in a format that provides their number in horizontal scale and the two-way-time in vertical one. These views are called radargrams.

During data processing, complex algorithms are applied. They remove noise or interference that may arise during acquisition: the band pass filters (vertical filters) are used to eliminate high and low frequency anomalies that occurred during the data acquisition (BUCKER et al. 1996, FISCHER et al. 1994); the AGC (Automatic Gain Control) normalizes the amplification and also removes reflections generated by noise due to the different signal attenuation (VALLE et al. 2000); F-K filtering transforms the reflections recorded in terms of time in the reflections in terms of frequency; the deconvolution allows to obtain an improvement of the resolution as it recovers bandwidth lost to attenuation phenomena; migration remove distortion caused by the wide range of propagation and is primarily used for the focusing of the reflection hyperbole (FISCHER et al. 1992, 1994, MILLIGAN & ATKIN 1993, MALAGODI et al. 1996). In this work processing data is carried out through an interpolation data with an experimental software. Thus a three-dimensional matrix is generated and represents the data volume to the chosen 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 slices, low amplitude variations express small reflections from the subsurface and, therefore, indicate the presence of fairly homogeneous material. High amplitudes denote significant discontinuity and often show the presence of buried objects in the subsoil or cracks and ruptures in the stonework. A definite change between high and low amplitudes may indicate the presence of a buried interface between two media.

ERT at historical centre of Frigento (Avellino, Italy)

The historical centre of Frigento (Avellino, Italy) is an example of a redevelopment project aimed at the knowledge and the enhancement of archaeological and historical cultural heritage of the village. Here different roman cisterns are situated into the subsoil (fig. 1). They date back to the Republican Roman age and consist of a set of tunnels and water collection wells which, from the groundwater of ridges, emerge from one of the highest points of the town. The Roman cisterns are located in the top of the promontory, in the historic centre of the village. In this area the archaeologists have brought to light many Roman and pre-Roman remains. The entrance of the Roman cisterns is located on a square and leads to one of the four cisterns through a ladder. The others are connected to the first cistern by low passages marked by stone arches made of regular ashlars.

Fig. 1 – Frigento (Avellino, Italy): a) Location of the survey area. b) Particular of tunnels. c) View from the inside of a Roman tank.

The cisterns are parallel to each other and located at the same altitude. The wall structure is in *opus incertum*, built with great care, and in some places it is almost *reticulatum*. All rooms have vaulted ceilings. The Roman cisterns were discovered in 1998 and at the moment three branches of the complex are restored and can be visited. Historical and literary sources describe a complex system of cisterns with eleven branches which lead to some wells, currently located in the gardens of private houses.
ERT was conducted inside one of those gardens in the need of higher depth of investigation (fig. 1).
In order to be able to represent data in horizontal sections, the investigated areas were properly covered by a grid of electric profiles which have to be densely prepared with the purpose to obtain an appropriate resolution. The whole resistivity data set was processed following a 3D tomography procedure that allowed

to obtain a tomospace of the investigated volume from which series of vertical sections and horizontal maps with increasing depth are extracted with the idea to better underline the spatial relationships among anomalies in the subsoil.

Figure 2 shows the real resistivity maps at four different shallow depths below ground level obtained using the 3D probability tomography method and including all the acquired profiles. In all horizontal real resistivity slices, mainly in the deepest slices at 2 m and 4 m depth, a highly resistive structure appears in the central part of the investigated area. It is probable that part of this anomaly is associated with the vault of one of the Roman cisterns. The low resistive anomaly which encloses the high resistive anomaly, visible in the third and fourth sections (3 m and 4 m depth), can be associated with the system of wells and galleries surrounding the cisterns, as indicated by historical sources and seen in the explored portion by archaeologists.

In order to better highlight the resistive anomalies in figure 3 a three-dimensional view of the investigated tomospace is presented. To outline the nature and shape of the resistive structures, a subspaces have been contoured using the mean resistivity value as cut-off resistivity and all of the resistivity values minor of it have been blanked. The highly resistive structure represents the three-dimensional reconstruction of the Roman cistern.

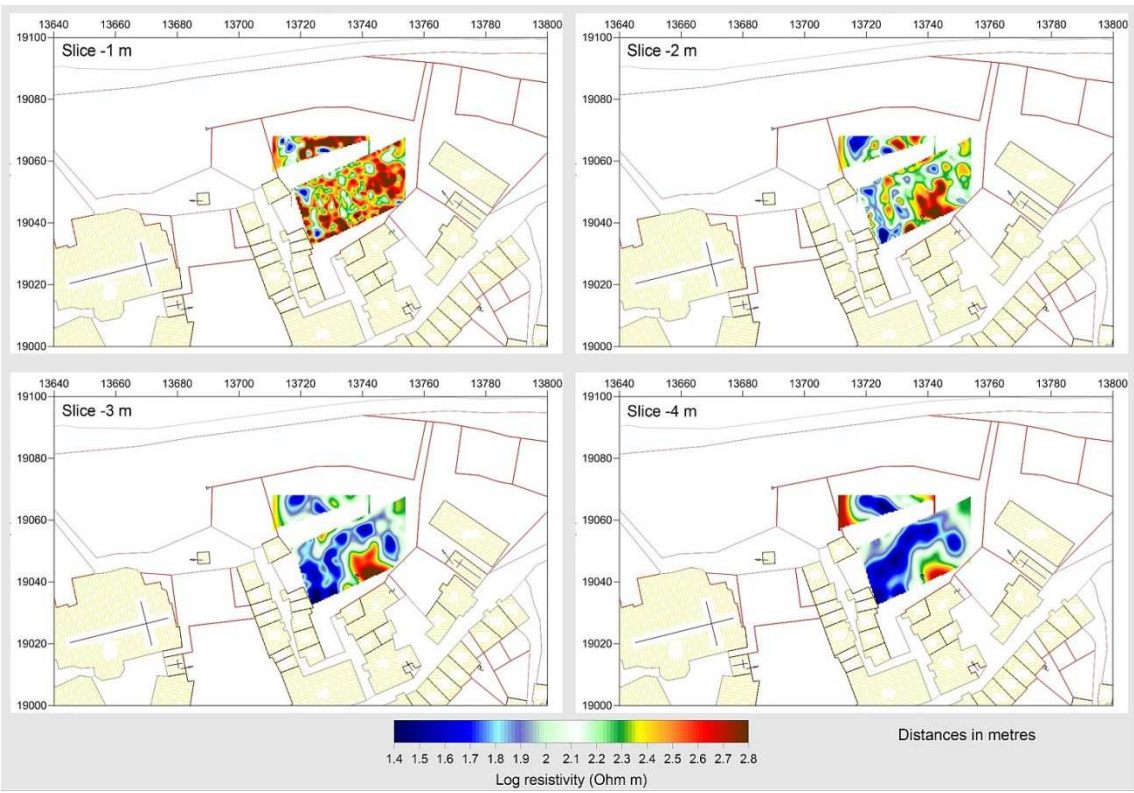

Fig. 2 – Frigento (Avellino, Italy): Electrical Resistivity Tomographies at four different depths below ground level.

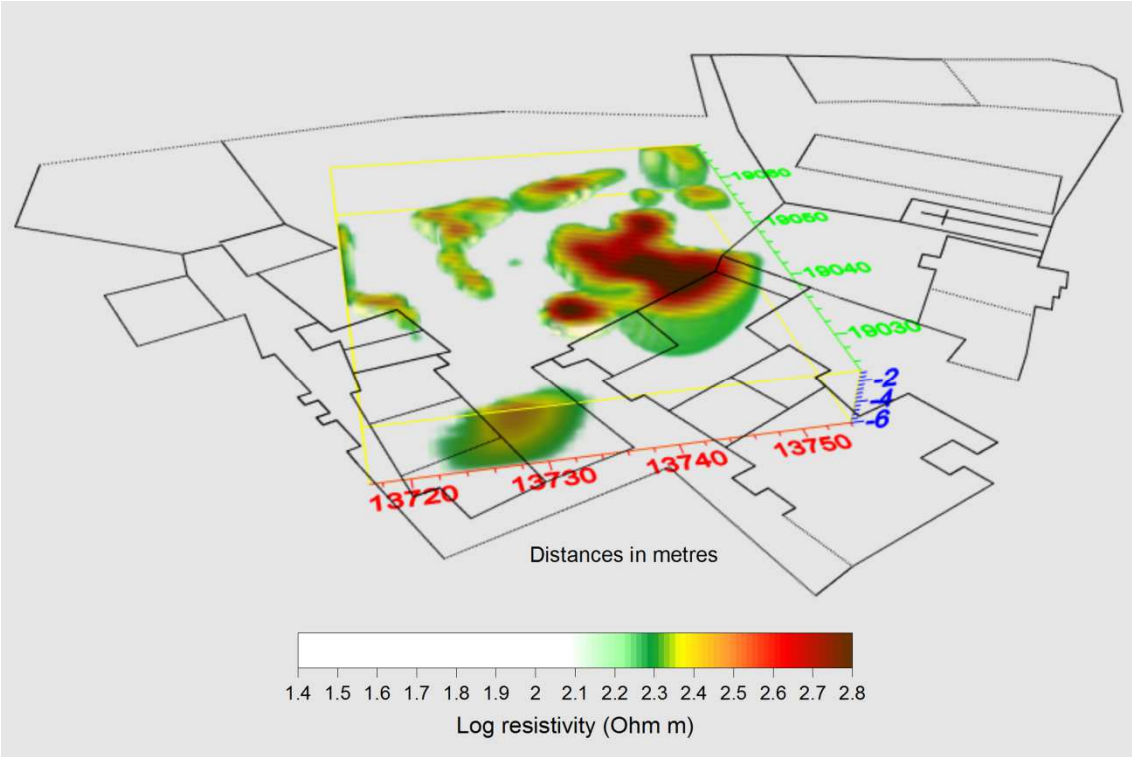

Fig. 3 – Frigento (Avellino, Italy): 3D view of the probability-based ERT representation.

ERT at the historical centre of Alife (Caserta, Italy)

Alife is a small village located in Central Italy which still retains the orthogonal urban structures of the Roman age enclosed by walls with a rectangular plant (540 m x 405 m) (fig. 4).

The currently visible walls are made in the lower part in *opus incertum* and date back to the Roman age, while in the upper part they date back to the medieval age. The height of the walls is about 7 m, of which 2 m are still buried into the soil. On each side of the city, there are a door and some posterns.

Fig. 4 – Alife (Caserta, Italy): a) Location of the survey area on aerial photo (L. M. Rendina). b) Data acquisition.

Here ERT diagnosis were carried out in the context of the feasibility study for the construction of a parish complex. The need of mapping the entire area for construction spread from its particular location within the historical centre well surrounded by the ancient city walls and the close distance from the Cathedral.
A complete and multi-layered map from 0.5 m to 5 m in depth was obtained performing different geoelectrical profiles, with axial dipole-dipole configuration, arrangements with 32-48 electrodes, mutual distance between electrode of 1 m and distance between profiles of 1 m. Figure 5a shows the sequence of vertical resistivity tomography obtained in the early investigation step. The main evidence is the presence of a number of surface anomalies (in the first metre in depth) and a well aligned system of high resistivity anomalies deeper down (starting from 2 m up to about 4 m in depth), whose geometry suggests the presence of underground chambers.

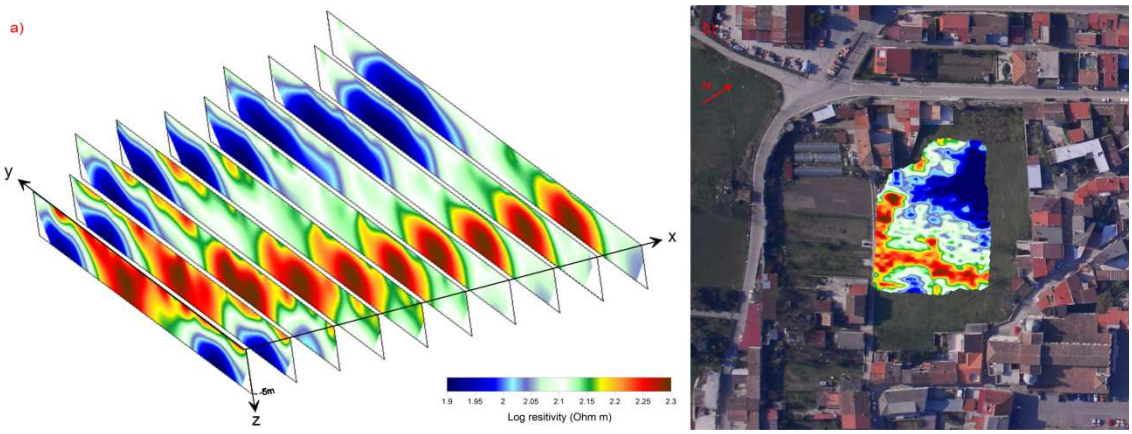

Fig. 5 – Alife (Caserta, Italy): a) Vertical Electrical Resistivity Tomographies. b) Resistivity map at 2 m in depth below ground level.

Different real resistivity maps at varying depths below ground level were obtained using the 3D probability tomography method including all the acquired profiles. The most interesting horizontal map is the one relative to 2 m in depth (figure 5b) where the presence of an high resistivity system stands out, with approximately straight trend, composed by a very regular alignments. The anomaly shape and its depth, related to the presence of well-defined anomalies in the vertical tomography, suggests the presence of caves (for example collector or tunnel). The low resistivity zone could be characterized by the absence of structures.

GPR and ERT survey at the historical centre of Nicosia (Cyprus)

In the frame of the archaeological mission supported by the Ministry of Foreign Affairs and in collaboration with the Nicosia Master Plan, a series of geophysical surveys were performed in order to show the applicability of non-invasive techniques for the diagnosis of historic buildings and for mapping the territory of Nicosia (Cyprus) in a predictive way in areas meant for public buildings. The project involved the investigation of different sites and we report in this work five examples.
The first survey concerned the monumental complex of the Bedestan located on the Turkish side of the walled city of Nicosia. Historical sources report that the Bedestan was built on the ruins of a sixth century Byzantine basilica, but the shape, size and location of the earlier church have always remained uncertain. A plan of consolidation and conservative restoration of the Bedestan complex was approved in 2004.

The prior phase of the project consisted in the analysis and evaluation of the modifications undergone by the building in the course of time. A stratigraphic analysis of the exposed walls of the complex allowed the various construction phases from the 10th century onwards to be geometrically delineated. However, no clear physical evidence emerged from this analysis as regards the presence of the earlier basilica. For this reason, we were asked to plan a geoelectrical resistivity tomography survey in order to identify traces of the presence of the earlier basilica beneath the floor of the Bedestan complex.

The ERT survey inside the Bedestan area was performed using a dipole–dipole array. Two perpendicular sets of profiles were arranged and a data set of about 17000 datum points was collected. Different real resistivity maps at increasing depths below ground level were realized. Figure 6 shows the slice at 1 m depth and it clearly puts into evidence the shape of a church characterized by a central nave with an apse and two side aisles that have been interpreted as an evidence of the existence of remains of the earlier Byzantine basilica (COZZOLINO et al. 2012). Excavations down to a depth of about 0.5 m in the area marked A have, as predicted, brought to light the existence of blocks of masonry.

The second survey involved the historical building placed near Famagusta Gate (fig. 7).

In a wall of the building the conservation status of sample areas of plaster and the presence beneath them of different historical phases of construction were assessed. The survey was carried out using the georadar with an antenna of 250 MHz in frequency. During data acquisition the antenna was moved on the walls on several lines placed at a mutual distance of 0.3 m. In order to have the higher number of measurements lines, the operations were conducted both vertically and horizontally on the walls.

The main evidence is a substantial lack of homogeneity in the texture of the wall between the bottom (anomaly A) and the top. At the top there are also some discontinuities (anomaly B) probably related to the presence of small fractures (COMPARE et al. 2010).

The third site was located in Plateia di Marche. The survey had the purpose to verify the presence of archaeological remains into the subsoil. The area was interested by an expansion of the present building and, as it is very near to an archaeological site, the probability to intercept ancient structures was very high. Thus, very close to the building of the market, ten geoelectrical profiles were performed with a length of 30 m and were placed at a mutual distance of 1.5 m. Here we show, for example, the electrical tomography section realized at 1 m in depth (fig. 8).

In the figure some high-resistive anomalies can be observed. They seem to have a circular or oblong shape, and with a pink line we define a hypothetical average trend. Some of these anomalies tend to cluster in an high resistive area, with fairly well defined geometric shape. Furthermore we can see a large conductive anomaly positioned exactly under a tower used for the distribution of water. It could be related with the surface of a possible tank of water and it is indicated with a pink circle. Also, the low resistive anomaly (colour blue), immediately above the circle, is certainly to be connected with the excavation carried out in that area. The conductive zone in the eastern part of the figure shows a well defined geometric shape, very differently orientated respect to existing modern buildings. We have suggested to verify if this trend, indicated by the pink line, may have correlations with the topography of ancient cities, as can be seen for example in the near archaeological site. The pink line represents the border between the most conductive and highest resistive area, indicated with a white colour.

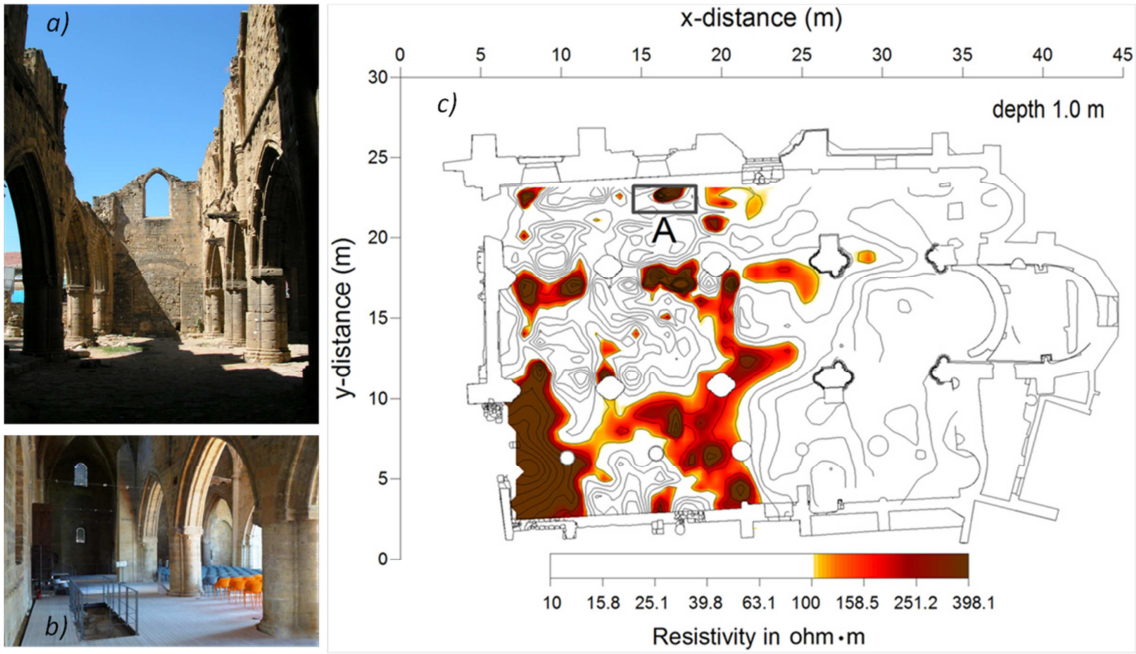

Fig. 6 – Nicosia (Cyprus): a) The Bedestan complex before restoration. b) The Bedestan complex after restoration, with exposure of foundations of the Byzantine church's peripheral wall, discovered in the rectangular area marked A in (c) (from www.whatson-northcyprus.com). c) The modelled resistivity map at 1 m depth. The rectangle marked A indicates the area where excavations have been carried out.

Fig. 7 – Nicosia (Cyprus): The Hospice near the ancient Gate of Famagusta (left) and georadar tomographies (right).

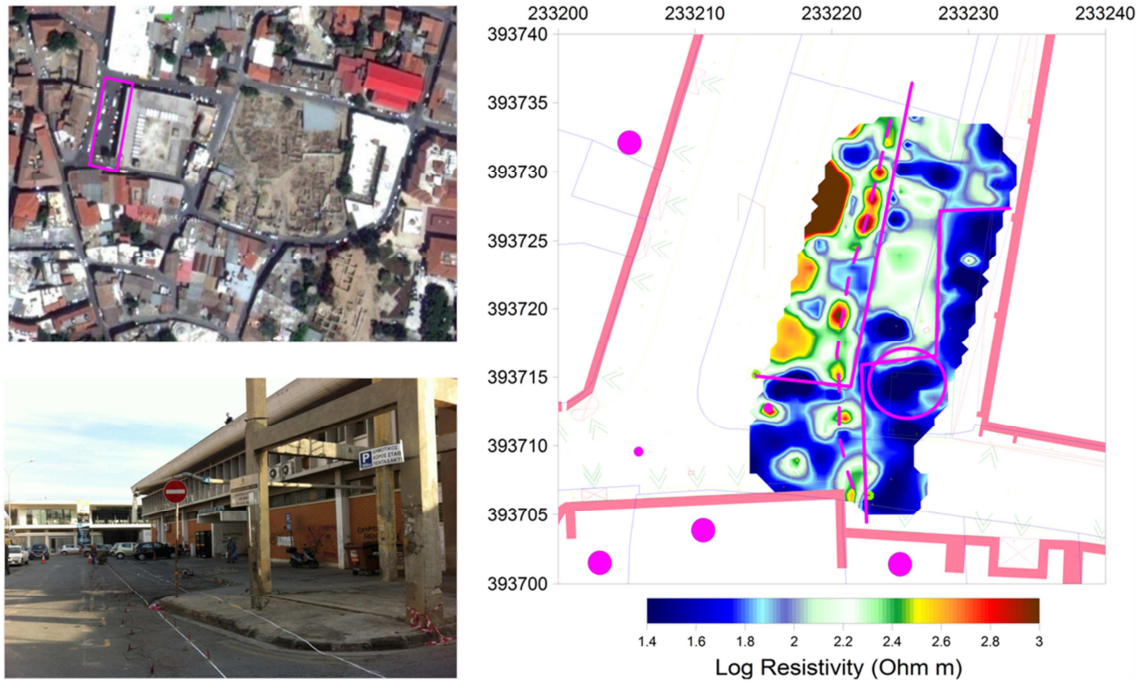

Fig. 8 – Nicosia (Cyprus): Plateia Di Marche (left) and Electrical Resistivity Tomography relative to 1m in depth (right).

The fourth site was located near Casteliotissa Hall (fig. 9). Here some historic ruins are visible and in particular a wall seems to continue under the road. In order to confirm this hypothesis, three geoelectrical profiles were performed placing the electrodes at a distance of 1 m, along lines of 30 m. Resistivity tomographies show that, in correspondence of the ancient hall, there is the presence of an high resistive anomaly at about 1 m in depth up to 3 m. Other two anomalies are visible at a depth of about 3 m, which can be interpreted as the presence of other two small parallel walls.

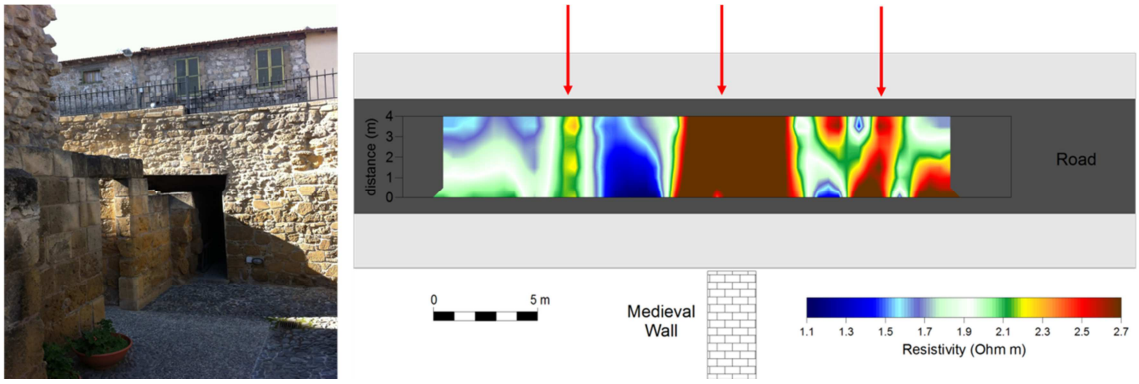

Fig. 9 – Nicosia (Cyprus): Casteliotissa Hall (left) and Electrical Resistivity Tomography relative to 3 m in depth (right).

The last site was located at Eleftheria Square (fig. 10). Also in this case the purpose of the survey was to verify the presence of ancient walls. Different geoelectrical tomographies were performed and in this figure the tomography relative to 2 m in depth is shown. We can note the presence of different high resistivity nuclei which are probably associated with the presence of ancient walls. Archaeological excavations brought to light some traces of the venetian walls.

Conclusions

This work showed different examples of the application of geophysical methods in case studies concerning the valorisation and restoring of the historical centres. In general, urban centres are points heavily modified by man and it can often be very difficult to pursue investigations and remove disturbing factors.
However we have demonstrated that geophysical results provided valuable information about the presence of areas of billing or buried alignments determining the depth of location of anomalous bodies and the definition of the overall site. Thus the use of these methods was helpful for the redevelopment projects, monitoring of ancient building for restoration actions, systematic works and valorisation actions of relevant elements. They allowed on the one hand the preservation and valorisation of ancient history of historical centres and on the other hand to carry out targeted choices for the urban transformation of territory.

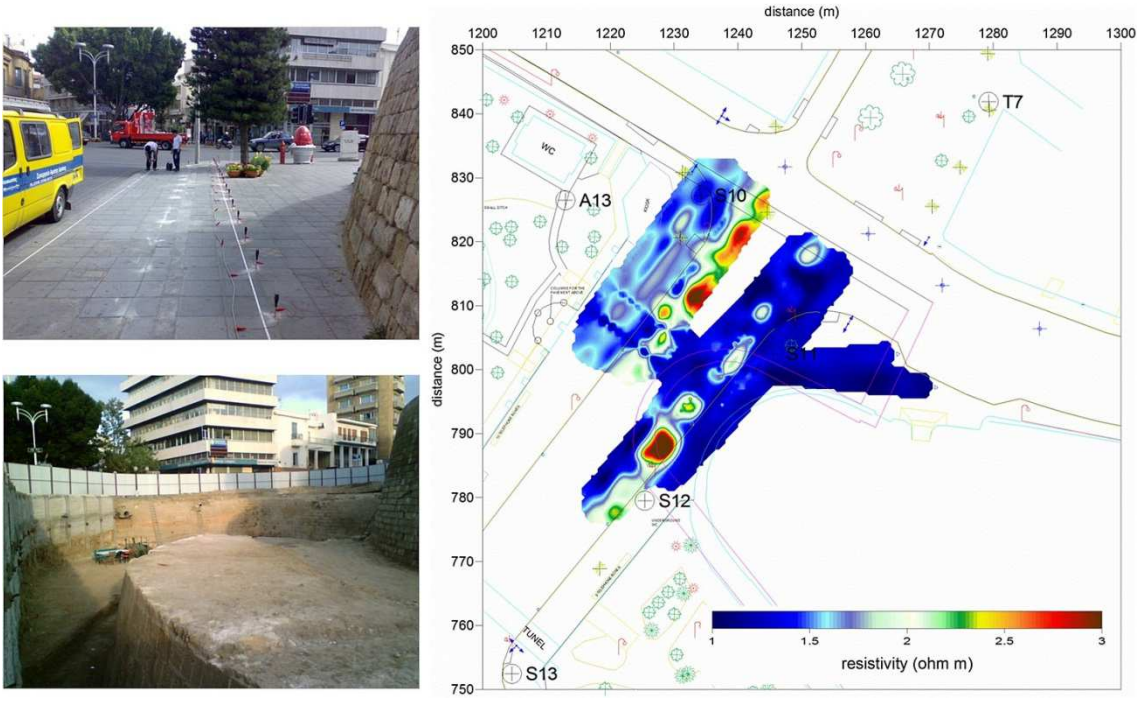

Fig. 10 – Nicosia (Cyprus): Electrical Resistivity Tomography relative to 2 m in depth (right), data acquisition (left, top) and venetian walls brought to light during excavations (left, bottom).

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Imprint:

Proceedings of the 19th International Conference on Cultural Heritage and New Technologies 2014 (CHNT 19, 2014)

Vienna 2015

http://www.chnt.at/proceedings-chnt-19/

ISBN 978-3-200-04167-7

Editor/Publisher**:** Museen der Stadt Wien – Stadtarchäologie

Editorial Team: Wolfgang Börner, Susanne Uhlirz

The editor’s office is not responsible for the linguistic correctness of the manuscripts.