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Application of ERT and GPR geophysical testing to the geotechnical characterization of historical sites

de Silva Filomena[1], d'Onofrio Anna[1], Evangelista Lorenza[1], Fascia Flavia[1], Silvestri Francesco[1], Scotto di Santolo Anna[2], Sica Stefania[3], Cavuoto Giuseppe[4], Di Fiore Vincenzo[4], Punzo Michele[4], Scotto di Vettimo Paolo[4], Tarallo Daniela[4]

[1] University of Naples Federico II, DICEA, via Claudio 21, Napoli (Italy) filomena.desilva@unina.it, anna.donofrio@unina.it, lorenza.evangelista@unina.it, flavia.fascia@unina.it, francesco.silvestri@unina.it
[2] Pegaso University, Piazza Cenni 2, Napoli (Italy), anna.scottodisantolo@unipegaso.it
[3] University of Sannio, Piazza Roma 21, Benevento (Italy), stefsica@unisannio.it
[4] National Research Council (CNR) - Institute for Coastal Marine Environment (IAMC), Calata Porta di Massa, Napoli (Italy), giuseppe.cavuoto@iamc.cnr.it, vincenzo.difiore@iamc.cnr.it, michele.punzo@iamc.cnr.it, paolo.scotto@iamc.cnr.it, daniela.tarallo@iamc.cnr.it

Abstract **– The paper presents two recent examples of application of Electrical Resistivity (ERT) and Ground Penetrating Radar (GPR), for reconstructing buried subsoil and structural geometries in two historical sites in the city of Napoli. Both investigation sites were characterized by complex environmental and logistic conditions. The first case study was an ancient hypogean cavity excavated in the tuff, where the integration between ERT and GPR allowed to identify the depth of the soft rock below the natural and anthropic filling. The second investigation was finalized to detect the foundation geometry of a high monumental bell tower resting on loose alluvial and pyroclastic soils. In both cases, the joint interpretation of ERT and GPR tests confirmed the preliminary knowledge on the subsoil and addressed further direct investigation aimed at the stability and safety of the two historical sites.**

I. THE EXPERIMENTAL TECHNIQUES

The paper presents recent examples of application of near-surface geophysical techniques, such as Electrical Resistivity (ERT) and Ground Penetrating Radar (GPR), in order to show their effectiveness in reconstructing buried subsoil and structural geometries in historical centres. In fact, such non-invasive methods can assist the geotechnical engineers in the detection of shallow subsoil conditions and foundation geometry when cultural heritage needs to be preserved and penetrating investigation tools (such as boreholes) must be avoided or, at least, their impact reduced to the minimum.

A. Electrical Resistivity Tomography

The Electrical Resistivity Tomography (ERT) consists of the experimental determination of the apparent resistivity ρ of a given material, through joint measurements of electric current intensity and voltage introduced into the subsoil through separate couples of electrodes ('dipoles'), driven in the ground surface. By deploying a linear array of dipoles, and recording the electrical signals for an acquisition time of the order of one hour, it is possible to back-figure a 2D pseudo-section, which can be subsequently turned into an actual resistivity section, with an investigated depth of the order of one fifth of the array length; of course, the longer the array, the higher the depth, but increasing the electrode spacing the resolution decreases.

The resistivity distribution can be interpreted in terms of soil lithology and saturation, taking into account that ρ increases with grain size, cementation and moisture. The ERT is most frequently used for the characterization of the layering and the lithological properties of soil and rock deposits involved in natural geo-hazards, such as slope stability, seismic response analyses, and monitoring of waste disposals or polluted sites. Few applications, on the other hand, are documented for soil-structure interaction problems.

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In the experimental campaigns reported hereafter, the ERT data have been gathered through electrodes of length equal to 40 cm, partially driven into the ground. The electrodes were then connected through multichannel cables, adopting the Wenner-Schlumberger [1] array configuration (Figure 1). This type of arrangement is hybrid between the Wenner and Schlumberger arrays: during the acquisition, the wiring is continuously changed so that the spacing *a* between the 'potential electrodes' remains constant, while that between the 'current electrodes' increases as a multiple *n* of *a*.

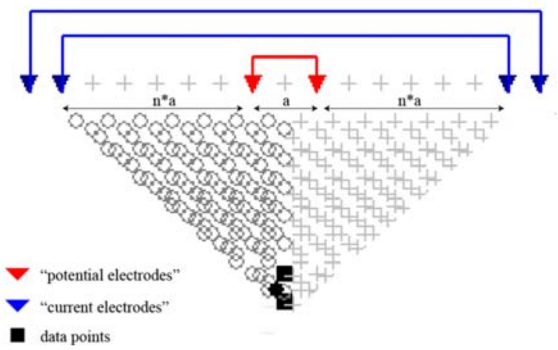

Fig. 1. ERT: Wenner-Schlumberger array configuration

The choice of such an arrangement was due to the need to study areas in which both lateral and vertical variations of resistivity are present. The resulting horizontal distribution of the underground data points in the pseudo-section, in fact, is comparable with that typical of the Wenner array, but their vertical resolution is better.
The geoelectric measurements of resistivity were executed with the georesistivimeter "SYSCAL Pro" (Iris Instruments™), and the resistivity data inversions were iteratively carried out through the RES2DINV software [1]. The inversion procedure uses a smoothness-constrained least-squares routine implemented into Occam's optimization algorithm, which permits determining iteratively a 2D resistivity model for the subsoil.

B. *Ground Penetrating Radar*

In order to characterize the stratigraphy of the subsoil and, in particular, to reveal the presence of natural and/or anthropic buried structures (such as crypts or graves), Ground Penetrating Radar (GPR) investigation was carried out. GPR uses a high-frequency electro-magnetic pulse transmitted from a radar antenna to probe the earth. The transmitted radar pulses are reflected from various interfaces within the ground, and this return is detected by the radar receiver (Figure 2). The dielectric properties of materials correlate with many of the mechanical and geologic parameters of materials [2].

A GPR system is made up of two main components: the control unit and the antenna. The control unit contains the electronics which triggers the pulse of radar energy that the antenna sends into the ground. The antenna receives the electrical pulse produced by the control unit, amplifies and transmits it into the ground or another medium at a particular frequency. This latter is the major factor affecting the investigation depth: the higher the frequency, the lower the pulse wavelength, hence the shallower the penetration. On the other hand, a higher frequency antenna has a better measurement resolution and will detect smaller targets.
The GPR investigations were performed by using a Subsurface Interface Radar System-3 (SIR-3000) manufactured by Geophysical Survey System (GSSI). A 270 MHz centre frequency antenna was used; this allowed to investigate the soil to a depth of about 5 m. The following acquisition parameters were selected: data word length, 16 bit; samples per scan, 512; recording time window, 94 ns; dielectric constant 8.
The obtained data were analyzed and filtered by using the commercial software "Radan 7", from GSSI, which produces radargrams purged by any anomalous signal caused by the presence of eventual interference.

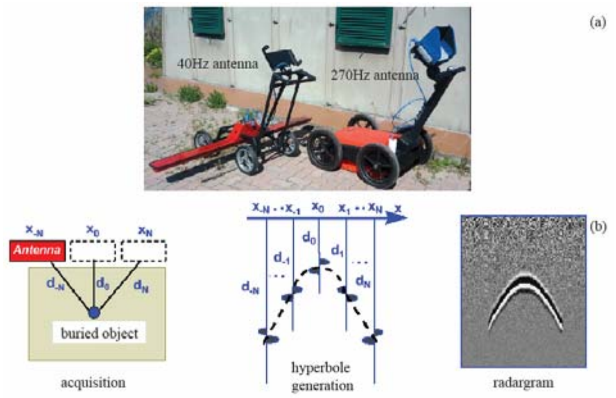

Fig. 2. GPR test: (a) equipment, (b) acquisition and interpretation of experimental data

II. RESULTS

The results reported in the following refer to field surveys carried out in two historical sites in Naples, currently under study by the researchers of the Universities involved, in close co-operation with the geophysical team of the Institute for Coastal Marine Environment (IAMC) of National Research Council (CNR), which provided the experimental equipment and know-how.

A. *Cimitero delle Fontanelle*

The first site is the "Cimitero delle Fontanelle", a cavity network made by chamber and pillars, one of the most fascinating hypogean sites excavated for the exploitation of the Neapolitan Yellow Tuff, whose origin may be traced back in the XVI century. The quarry became a charnel house after catastrophic events such as earthquakes and plagues in the XVII century (Figure 3).

The cavity roof, as high as 10 m, is supported by 9 isolated pillars and 4 further vertical elements, defined 'septums', protruding from the walls. The overall shape in plan is rectangular, elongated in the NS direction and consisting of three naves, just like a church.

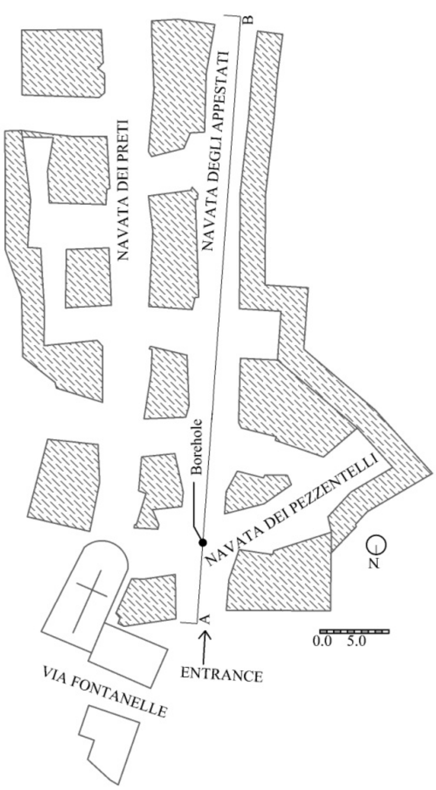

Fig. 3. Plan view of the Cimitero delle Fontanelle and location of borehole, ERT and GPR surveys.

The nave sections have a trapezoidal shape with a flat roof and walls inclined 10° – 15° with respect to the vertical; the pillars, consequently, have a structural section decreasing with depth (Figure 4a). The only borehole available shows that the material below the current floor level (71.50 m a.s.l.) is composed by an inter-bedding of anthropic fill and natural soils of different grain size, with both volcanic and alluvial origin (Figure 4b). The tuff formation, covered by cuttings resulting from the excavation, was detected at a depth of 9.0m from the current walking level: it is therefore believed that the pillars are buried in the filling material for a significant stretch. Preliminary numerical studies, carried out in order to evaluate the stress state of the cavity [3],[4], showed that one of the major uncertainties is connected to the actual height of the pillars, i.e. the hidden geometry below the current floor, closely related to the unknown details of the excavation technique.

According to the reconstruction of the sequence of events, a mixture of tuff cuttings, debris and mud transported by the floods gradually have been accumulated on the bottom of the excavation, where human remains were buried or simply abandoned by the gravediggers.

ERT tests have been carried out with 48 electrodes using the above mentioned Wenner-Schlumberger array configuration. The main alignment investigated along the main gallery, the so-called "Navata degli Appestati" (AB in Fig. 3), encompassing a length of 94 m with 2 m electrode spacing. A total number of 3006 measurements have been attained, which were inverted to obtain the section reproduced in Figure 4b down to an investigation depth of about 10 m.

The 2D image shows apparent resistivity lateral changes, confirming the complexity of the buried geometry. Overall, it is possible to individuate:

- a shallow layer, about 2 m thick, characterized by a range of resistivity of 100-500 Ωm which can be associated to the anthropic coarse fill ('acf');
- an intermediate layer, 2 to 4 m thick, with a lower resistivity (about 10-100 Ωm), corresponding to the volcanic-alluvial sand and silt ('ss') formation detected by the borehole down to 4m depth;
- a deeper layer where the resistivity suddenly increases to values between 500 to 1000 Ωm, typical of soft rocks like the Neapolitan Yellow Tuff ('NYT').

Note that close to the middle of the gallery, a sharp decrease of resistivity down to about 10-60 Ωm appears also in the shallowest 'acf' layer: it can be interpreted as the presence of a moister zone associated to visible water leaks from the cavity roof. Also, while the smooth horizontal variation along the deeper 'ss' layer can be again attributed to changes in the degree of saturation, the sharper discontinuities in the 'NYT' tuff formation can be associated either to its fracturing or to the presence of the cuttings ('NYTc').

Most of the above evidences are confirmed by the radargram recorded along the same alignment (Figure 4c): in fact, the uppermost 2 m (down to the dashed line) are characterized by a clear attenuation and scattering, respectively typical of wet and coarse materials. The intermediate radargram depths, ranging between 2-3m (southern side) and 2-4m (northern side), corresponding to the 'ss' layer, appear quite regular and well stratified. The strong reflector (solid line) in the GPR profile represents the transition from the sand and silt layer to the tuff formation.

From both tests, still some uncertainties remain on the actual depth of the intact Neapolitan Yellow Tuff formation buried below the cuttings, and on the anomalous zone characterized by an increase of resistivity up to 3000 Ωm and to a chaotic zone in the GPR profile, which can follow from small diffraction hyperbolas, generated by objects smaller than antenna's horizontal resolution.

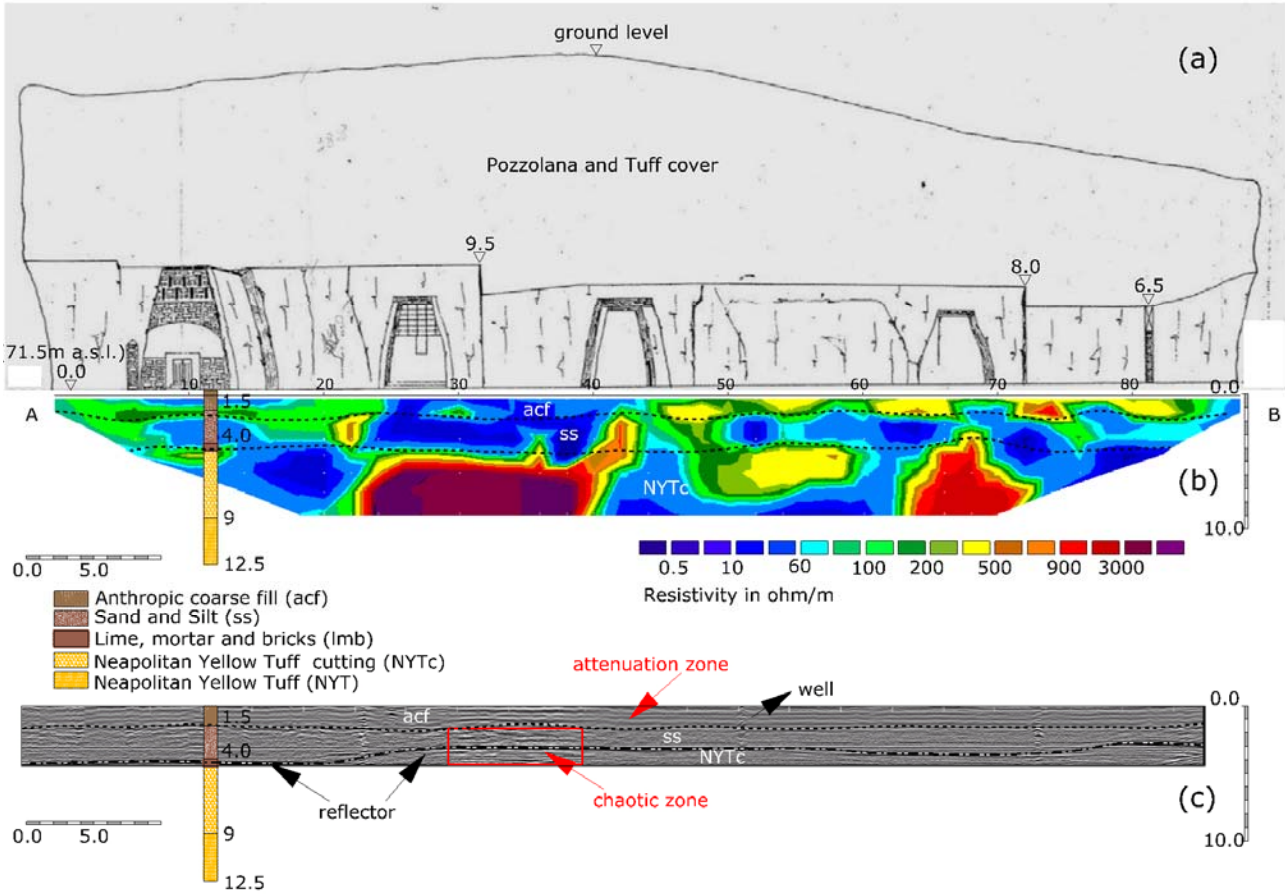

Fig. 4. (a) Cross section of “Navata degli Appestati”; (b) ERT tomography section and (c) GPR radargram.

B. *Carmine bell tower*

The second case study is the Carmine bell tower, adjacent to the neighbouring magnificent church in the Eastern seaside area of Naples (Figure 5), subjected to a considerable seismic hazard. The current structure, in fact, was built during the XVII century on the basement of a former bell tower, destroyed by the Sannio earthquake in 1456. The brickwork structure, 68 m tall, is characterized by a rectangular cross section, made up of Neapolitan yellow tuff, from the ground level up to the height of 41 m (Figure 6a). The upper part, completed by a spire, has an octagonal cross section made up of clay bricks. The bell tower rests on a very deformable deposit of man-made ground and alluvial sands, overlying volcanic tuff [6].

In order to preserve the monument by future earthquakes, significant mitigation countermeasures may be necessary. Thus, the fine tuning of the seismic protection requires analyses on refined models, based on the deep knowledge of the structure, its foundation and the underlying soil, in order to catch the dynamic soil-structure interaction behaviour in a more realistic way [7].

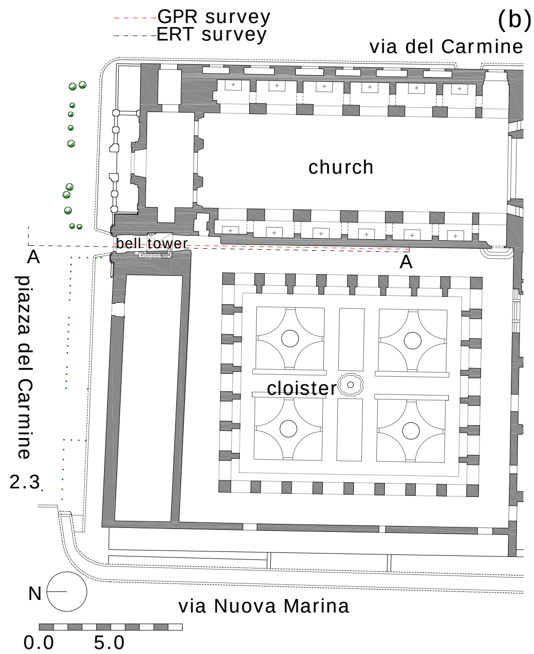

Fig. 5. Plan view of the Carmine bell tower and location ERT and GPR surveys.

The structural model was calibrated according to stress measurements in the masonry, carried out with flat jacks [8], and to the dynamic identification, performed by recording the free oscillations with instruments located at different levels [9]. Insofar, the geotechnical model was reconstructed on the basis of existing data nearby the site [6]: the subsoil consists of a very deformable deposit of made ground (5m on the average) and alluvial sands (down to about 20m), overlying volcanic tuff.
On the other hand, the shape and the depth of the foundations were not yet investigated to date.

According to similar Italian cases of towers overlying deformable soil ([10], [11], [12]), in the previous studies the foundation was supposed to be a shallow footing characterized by roughly the same shape as the ground floor plan, i.e. a bare enlargement of the corresponding superstructure walls.
Both ERT and GPR surveys were performed along the base of the tower and the church, crossing the tower masonry walls through two openings, in order to achieve the maximum investigation depth under the tower itself (Figure 6b).

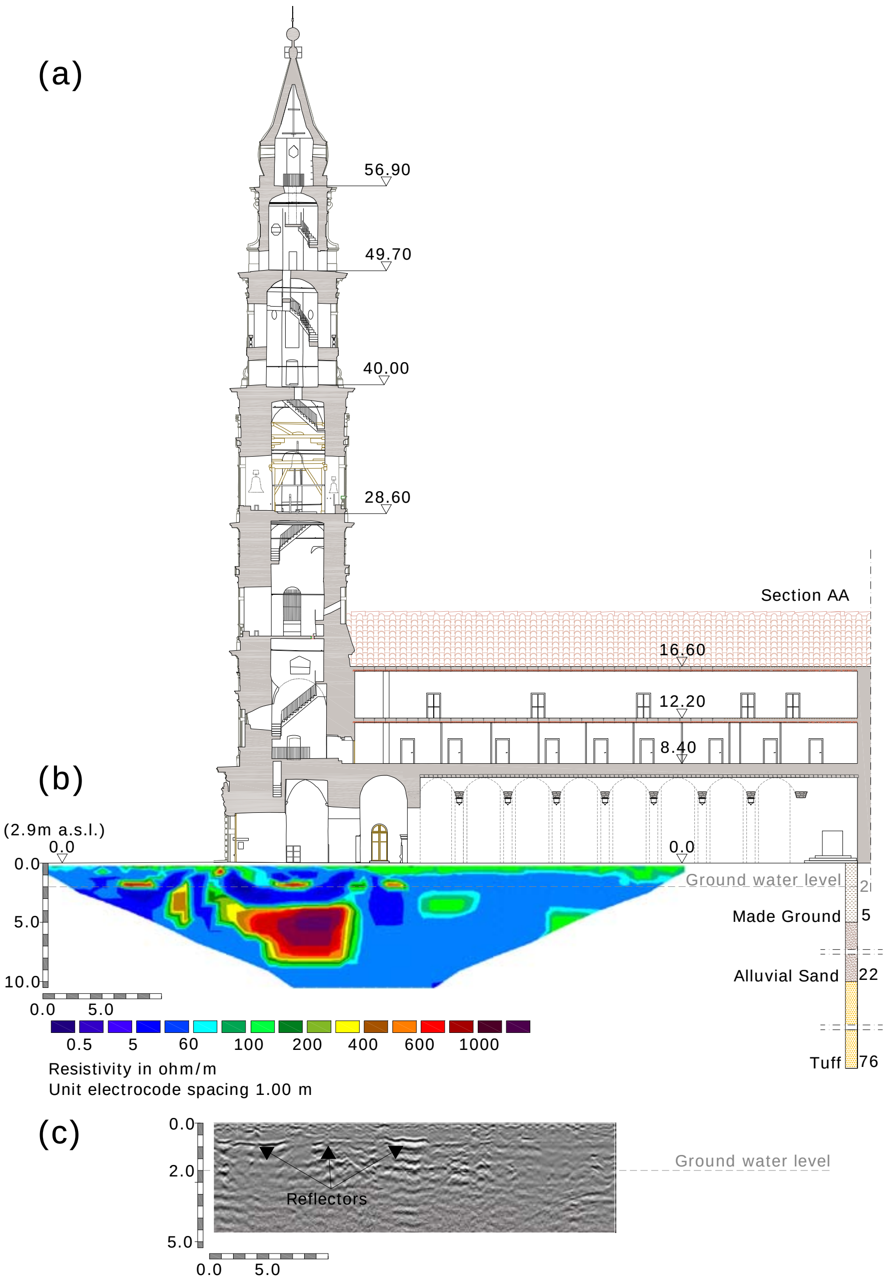

Fig. 6. (a) Cross section of Carmine bell tower; (b) ERT tomography section and (c) GPR radargram.

In this case, the electrode stakes were set with 1m spacing along a 40 m alignment, starting from Carmine square until the middle of the church wall adjacent to the cloister (Figures 5-6). This array configuration yielded a 2D tomography characterized by 3006 measurements, reaching a maximum depth of about 10 m in the stretch where the foundation was expected to be located.

The ERT clearly highlights an area of high resistivity (more than 600 Ωm) as wide as 10 m, extending from a depth of 4 m until a maximum of about 8 m (Figure 6b). Being this area located just beneath the structure of the bell tower, and since the resistivity values are similar to those measured in the NYT in the other site, the anomaly can be ascribed to the foundation shape. Similar evidences could not be detected in the GPR profile (Figure 6c) due to the low depth reached (maximum 4 m); the presence in the radargram of a well-defined and continuous reflector at a depth of about 0.8 m just outside the bell tower (chainages 0-6 m and 14-18 m) might identify an old floor level.

It is also interesting to observe in the ERT the presence under the church wall of a 1-2m layer, characterized by resistivity values between 150-200 Ωm and overlying a formation with higher conductivity, with values of the order of 50 Ωm, comparable to those detected above the tower foundation and in the shallow soil outside the building. The presence of this high resistivity zone can be attributed to the vicinity of the church wall foundation. The effects of changes in soil saturation, expected to result into a sudden decrease of resistivity across the groundwater depth of 2m, are more evident outside the building than inside it: in fact, on this side the groundwater conditions may be influenced by a pumping system operating in the hypogean rooms underneath the church apse; moreover, the monolithic foundation may represent a watershed inducing a damming effect.

III. CONCLUSIONS

Summarizing, both case studies demonstrated the effectiveness of the individual and the combined ERT and GPR techniques to map subsurface contrasts between zones with different conductivity relevant to different geomaterials or foundation elements, and to describe the local variations of groundwater conditions, when present.

The results of ERT and GPR surveys represent significant reference information for both sites, in order to better address further direct investigations (e.g. borehole and S-wave velocity measurements) to assess the actual position of the original cavity floor at the Cimitero delle Fontanelle, and to confirm the depth and shape of foundation of the Carmine bell tower.

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