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An electric and electromagnetic geophysical approach for subsurface investigation of anthropogenic mounds in an urban environment

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ABSTRACT

Scientific interest in mounds as geomorphological features that currently represent topographic anomalies in flat urban landscapes mainly lies on the understanding of their origin, either purely natural or anthropogenic. In this second circumstance, another question is whether traces of lost buildings are preserved within the mound subsurface and can be mapped as remnants testifying past settlement. When these landforms have been modified in centuries for civilian use, structural stability is a further element of concern. To address these issues we applied a geophysical approach based on a very low frequency electromagnetic (VLF-EM) technique and two-dimensional electrical resistivity tomography (2D-ERT) and integrated it with well-established surface survey methods within a diagnostic workflow of structural assessment. We demonstrate the practical benefits of this method in the English Cemetery of Florence, Italy, whose mixed nature and history of morphological changes are suggested by archival records. The combination of the two selected geophysical techniques allowed us to overcome the physical obstacles caused by tomb density and to prevent interference from the urban vehicular traffic on the geophysical signals. Eighty-two VLF-EM profiles and five 2D-ERTs were collected to maximise the spatial coverage of the subsurface prospection, while surface indicators of instability (e.g., tomb tilt, location, and direction of ground fractures and wall cracks) were mapped by standard metric survey. High resistive anomalies (>300 and 400 Ωm) observed in VLF-EM tomographies are attributed to remnants of the ancient perimeter wall that are still buried along the southern side of the mound. While no apparent correlation is found between the causes of tomb and ground movements, the crack pattern map supplements the overall structural assessment. The main outcome is that the northern portion of the retaining wall is classed with the highest hazard rate. The impact of this cost-effective approach is to inform the design of maintenance and restoration measures based on improved geognostic knowledge. The geophysical and surface evidence informs decisions on where interventions are to be prioritised and whether costly invasive investigations are needed.

1. Introduction

Urban geomorphology relates to the study of geomorphologic features — of natural, artificial, or mixed origin — in changing and growing urban environments. Geographically confined to areas of concentrated urbanisation (Thornbush, 2015), this discipline also aims to understand how these features reflect the human impact to transform natural terrain into anthropogenic cityscape. In the last 40 years a plethora of studies have investigated the processes and research methods to achieve this knowledge (Coates, 1976; Cooke, 1976; Ahnert, 1998; Bathrellos, 2007; Douglas, 2010; Hudson et al., 2015).

Historically, valleys and alluvial plains were among the preferred landforms to found towns and cities. Nonetheless, natural reliefs and low, rounded hills — the latter commonly referred to as 'mounds' — were exploited owing to their elevation compared with the surrounding flat landscape. These areas were mostly used to install defences, garrisons, or observation points. In other cases, they were considered ideal for civilian uses that needed to be kept separate from the rest of the urban layout, such as cemeteries.

Evidence of the human alteration of local natural features can still be recognised at the ground surface, if the landform is not fully hidden by urban sealing, or caused by those agents that Chengtai (1996) defined as 'artificial geomorphologic'. The public parks of Monte Mario and Colle Oppio in Rome and della Montagnola in Bologna, Italy, are examples of natural mounds and topographic reliefs in old cities that were reshaped and greened during interventions of landscape engineering and architecture in the nineteenth to early twentieth centuries. As a

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consequence, these mounds currently are perceived as green isles within the dense urban fabric and infrastructure built in the mid twentieth to early twenty-first centuries. These situations of mixed artificial and natural ground — compare with 'landscaped ground' definition according to the terminology by McMillan and Powell (1999), Price et al. (2004), and Ford et al. (2010) — can preserve stratigraphic information useful to reconstruct the history of settlement and use or buried remains of lost structures. In this sense urban geomorphology also meets the purposes of archaeological prospection, and this is the framework where this research sits.

The challenge is how to investigate the subsurface without being limited by the physical and environmental constraints and, at the same time, able to gather a sufficient amount of data of suitable resolution to assess the inner structure of the mound. Current morphology, configuration, use, and geographical location of the mound within the urban fabric are among the most common constraints to data accessibility. Furthermore, traditional methods of stratigraphic data collection typically consist of intrusive ground investigations, such as borehole drilling or test-pits and trenches, to expose the subsurface. Apart from being costly, these operations would represent a potential source of damage to the amenity and integrity of the historic assets.

The aim of this paper is therefore to present a geophysical approach based on electric and electromagnetic methods — i.e., very low frequency electromagnetic (VLF-EM) technique and two-dimensional electrical resistivity tomography (2D-ERT) — that can address these issues by exploring the subsurface of anthropogenic mounds in urban environments; relating the observed patterns with historical studies of the geomorphological evolution and surface indicators of ground instability; and finally, providing an evidence base that can inform the decision-making process to plan future ground investigations, maintenance, or repair works.

We implemented our method to the experimental site of the English Cemetery in the city of Florence, Italy. The key questions were: (i) the validation or confutation of the hypothesis that the inner structure of the mound still preserved a section of the perimeter wall formerly connected to the medieval city walls; and (ii) the assessment of the current structural stability of the mound.

As acknowledged by Vitek (2013), technology-led developments can advance field research in geomorphology studies. This paper goes in this direction to demonstrate that a combination of VLF-EM, 2D-ERT, and surface survey can be a viable approach to:

- characterise the structure and composition of the subsurface, thereby proving the archaeological anthropogenic nature of the urban mounds; and
- integrate the stratigraphic findings into the assessment of the structural stability of the mounds.

Notably, the integration of different geophysical methods (e.g., resistivity and VLF-EM: Khalil et al., 2010; Abbas et al., 2012) allows a better data interpretation and improves the level of confidence with regard to the observed patterns. The selection of the geophysical methods is a trade-off between their advantages and intrinsic limitations.

Ground penetrating radar (GPR) has been the most exploited technique in archaeo-geophysics and recently also in the field of nondestructive shallow (<10 m) subsurface forensic investigations (Barone et al., 2016, and literature therein) owing to its properties of high resolution, penetration depth, and fast and cost-effective application (e.g., Griffiths and Barker, 1994; Leckebusch, 2000; Gaffney, 2008; Drahor, 2011; Reynolds, 2011; Goodman and Piro, 2013). Nevertheless, GPR is not suitable for the applications considered in this paper because of: i) the geomorphological conformation of the mound (see Section 2.1); ii) the surface distribution and high density of the monumental tombs that make impossible the use of antennas that have to be coupled with the ground and/or the collection of parallel profiles according to a regular grid (Barone et al., 2016); and iii) the maximum penetration depth of a few meters.

On the other hand, the combination of VLF-EM and 2D-ERT is suitable for implementation in urban contexts where the anthropogenic mounds are surrounded by major city streets with high and constant traffic volumes, and the ground surface is dense with physical obstacles (e.g., poorly distanced tombs in burial ground). Both methods can provide information about the same physical parameter (the soil conductivity or its inverse, i.e., the resistivity); but while VLF-EM is faster, is not affected by physical obstacles, and can provide qualitative areal maps of the measured parameter, 2D-ERT offers higher resolution and provides quantitative information of the electrical properties of the soil. The capability of the VLF-EM to detect buried walls, small-scale conductive and complex structures, was tested by Khalil et al. (2010) and Abbas et al. (2012). In these studies, vertical electrical soundings were integrated with VLF-EM to recognise the general subsurface geoelectric succession and to use the average resistivity value of the media for purposes of a two-dimensional VLF-EM inversion.

This paper is structured as follows: Section 2 provides a description of the English Cemetery, with a complete historical analysis of the geomorphological evolution of the site as inferred from archival documents and paintings; Section 3 details the techniques and methodology; Section 4 presents the results of the geophysical and surface surveys and the data interpretation. The full picture of the subsurface is then discussed in relation to the map of the surveyed surface damages. The latter are used as indicators of the interactions between the artificial ground, exogenous physical agents (e.g., water runoff and infiltration) and current usage of the mound (in the case of the English Cemetery, burial ground with decomposition of organic materials and microcavity generation). Conclusions are drawn to underpin recommendations for strategic planning of preservation measures.

2. Experimental site: English Cemetery, Florence, Italy

2.1. Geomorphologic, geological, and geohazard settings

The English Cemetery of Florence lies on a vegetated mound located in Piazza Donatello (Lat 43.777°; Lon 11.268°) northeast of the town centre (Fig. 1A–B). According to the official cadastre, the oval shape of the cemetery extends NW-SE for >6000 m^2 (~120 m × 64 m; Fig. 1B). The elevation ranges from 51.8 m asl at the southeastern entrance to 58.1 m asl at the top of the northwestern head. Here the drop of ~7 m with regard to the ground level of the road pavement is enhanced by the perimeter retaining walls made of blocks of sandstone (Fig. 1C–D). Therefore, to those coming from the northwest along Viale Giacomo Matteotti, apparently the mound, alongside the neighbouring park of Villa Gherardesca (Fig. 1B), is the most remarkable topographic anomaly of the Florentine urban layout within the enclosure of the nineteenth century boulevards.

According to Tuscany Region (1994), fluvial flooding events are considered 'exceptional' to occur in the whole area. In such circumstances, given the geomorphology and topography of the mound, it is extremely unlikely that the mound itself and the tombs at the top can be flooded, except for the entrance and the southern end which are located at the lowest elevation.

From a point of view of urban geology, no borehole information was available to this study with regard to the Cemetery itself, neither have invasive ground investigations been carried out as part of this research (cf. Section 3), and the authors are not aware of any other previous geological prospection. The closest boreholes are those numbered 1312 and 1636 available from the Municipality WebGIS repository (Comune di Firenze, 2015a) that were drilled in two locations in Borgo Pinti and the park of Villa Gherardesca within a radius of about 200 m from the centre of the mound (Fig. 1B). These boreholes confirm a stratigraphic sequence of alluvial deposits that formed during the depositional