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Unusual Geophysical Techniques in Archaeology - HVSR and Induced Polarization, A Case History

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SUMMARY

Conventionally employed geophysical methods in archaeological investigations , i.e. ground penetrating radar(GPR), magnetometry, geoelectric (electrical resistivity tomography: ERT) and geo-electromagnetic (FDEM) techniques, can be hampered by specific site conditions. In the case history here presented, i) magnetometry was ruled out due to the presence of iron structures used to support nearby fences and greenhouses partially covering part of the site; ii) GPR employment was tested but not employed due to low penetration depth (i.e. presence of superficial clay sediments) which was much less than the depth of the target, iii) ERT, unfortunately, could not detect the paleo-surface(s) layer(s) as their thickness is below the resolving power of the method. For these reasons and keeping in mind that the paleo-surfaces could have been stiffened due to trampling of human activity over the centuries along which the settlement existed, we employed the Horizontal-to-Vertical Spectral Ratio method (HVSR) which is sensitive to the presence of appreciable contrasts of acoustic impedance of such paleo-surfaces. The obtained results have been proved by direct excavations. Likewise, the Induced Polarization tomography (IPT) which was acquired during the ERT survey, shed light on the presence of increased and well-organized chargeability values that inferred the presence of a paleo-riverbed.

Introduction

Archaeological surveys can take advantage of geophysical methods, which allow investigating large sites with the purpose of defining areas of interest for subsequent excavations, saving time and costs. The geophysical methods commonly used in archaeology are magnetometry, ground penetrating radar (GPR), electrical resistivity tomography (ERT) and low-frequency geoelectromagnetic methods, to retrieve an image of the distribution in the subsurface of magnetic susceptibility, dielectric permittivity and electrical resistivity or conductivity, respectively (see, e.g., Gaffney and Gater, 2003). However, the success of the survey depends on a proper choice of the investigation strategy, as different geophysical techniques characterize different physical properties and where one technique is successful others may fail (Hesse, 1999; Piro *et al*. 2000).

In the case history discussed here, the target of the archaeological research is to reconstruct two paleo-surfaces, partially overlapping, the most ancient one pertaining to the Bronze Age, while the latter to the Roman dominion. Previous excavations had detected the two cultural paleo-surfaces at depths ranging, from place to place, between 40 cm and 180 cm below ground level (b.g.l.). Each one is enriched by pottery remains. The archaeological area pertains to a “Terramara” (Desittère, 1997), located in the nearby of the Pilastri village in the eastern portion of the Po plain. The Bronze Age paleo-surface (also corresponding to the Roman surface in part of the archaeological area) is located on the top of a stratigraphic sequence formed by overlapping clay, silty-clay, loam and sandy layers whose structure has been partially reworked by agricultural activities. This area was conditioned by geomorphological changes throughout the last two millennia. During this time period, floods by the nearby Po River and its tributaries affected the area repeatedly, resulting in new deposits and presumably creating new riverbeds.

Therefore the recourse to geophysical techniques was both to detect remains and paleo-surfaces and to integrate the geological exploration of the subsurface to characterize its geomorphological evolution. Unfortunately, i) the site is also partially covered by intensive farming greenhouses, so that the use of magnetometry was excluded; ii) the paleo-surfaces are embedded in clayey sediments, capable of reducing GPR penetration well below the target depths, even using the lowest frequency available antennas; iii) the ERT technique is hampered by the specific geology of the site, because the thicknesses of the paleo-surfaces are most probably below the resolving power of the method. As is known, ERT may effectively detect a paleo-surface if it separates layers of different textures and thus characterized by fairly different resistivity ranges. Bearing that in mind and assuming that the paleo-surfaces could have been stiffened due to trampling of human activity over the centuries along which the settlement existed, we decided to test the Horizontal-to-Vertical Spectral Ratio method (HVSR: Nakamura, 1989) which is sensitive to the presence of discontinuities in the acoustic impedance (i.e. density and velocity of shear waves product). Such kind of settlements is not rare, as there are many “terramare” diffuse in the Po plain, and such issues (urban noise, conductive terrain) are common, as archaeological sites are very often located very near to modern towns.

Materials and methods

The archaeological site of Pilastri (province of Ferrara, Northern Italy) is part of the demographic phenomenon of the Middle Bronze Age (1700/1650-1350/1300 BC), known as “terramara” in Emilian plain (Desantis and Steffè, 1995). The typical terramara settlement is well documented in the literature as quadrangular in shape, surrounded by an embankment and a moat, often filled with water from a nearby stream. Inside, they were artificially flooded and houses were built on a wood platform.

In the frame of a “preventive archaeology” investigation, in 2013, five excavation surveys (A, B, C, D, E: Figure 1) were carried out to confirm the presence of the settlement, whose extent and state of preservation were only hypothesized in previous campaigns. The Bronze Age surface was found only for a certain length of the trenches while it disappears moving both to west in B and to east in C, giving way to Roman age levels. Both horizons extend in E-W direction over a width of about 100 m. Beyond these limits the settlement is bordered toward west by a series of floods which fill a natural depression, while to the east a clay matrix is encountered, characterized by a strong presence of large tiles and brick fragments from the Roman period, possibly filling the depression around the settlement (Balasso and

Michelini, 2013). Because a paleo-soil of Roman age was detected in trenches C, D and E showing a possible extension of the archaeological area toward East, it became of utmost relevance to explore the eastern side of the settlement (highlighted by a red polygon in Figure 1).

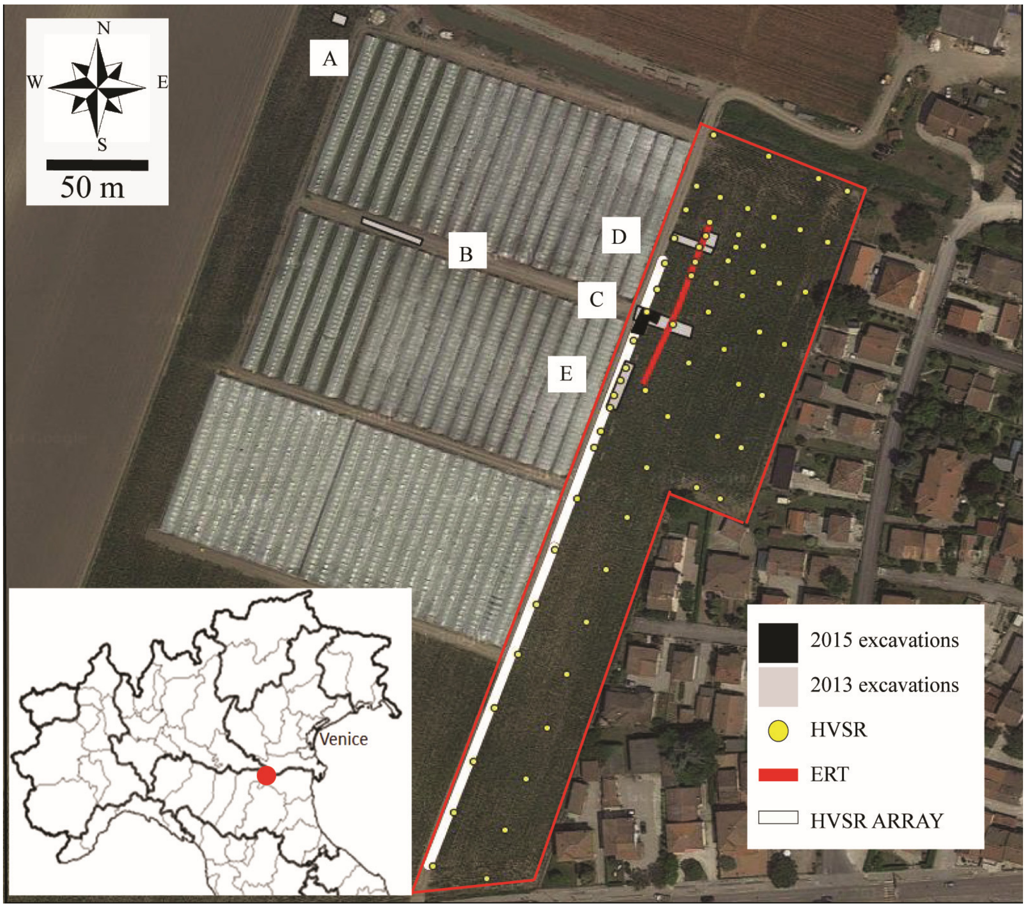

Figure 1 *Locations of geophysical measurements and of the 2013/2015 excavations.*

The principle of the HVSR method, widely used in the frame of micro-zonation studies, although very rarely, up to now, in archaeology, is as follows: the horizontal components of a seismic wave field at a site, whose subsurface is composed by a soft upper layers laying over a more rigid substratum, show an amplification at specific frequencies f_n, given by the following relationship:

$$f_n = \frac{V_S(2n-1)}{4h}, \; n = 1{,}2 \ldots . \infty$$

where V_S is the velocity of shear waves in the upper layer and h its thickness. If there are more discontinuities of increasing acoustic impedance contrasts, the ratio between the spectra of the total horizontal component and of the vertical component of the seismic motion shows as many resonance peaks. Input data is simply the ambient noise in the range of few tens of Hz, continuously recorded by a 3-component seismometer for a quarter of an hour or so.

Measurements and results

67 measurement stations were acquired, covering an area of about 12000 m^2, spaced 20 m each other and tightened to 10 and 5 m spacing around the trenches C and D (Figure 1). Spectra were then calculated using the free “GEOPSY” code (www.geopsy.com). Using a Matlab^R code specifically written, a 3D map was then constructed, by interpolating the spectra above the whole area and considering the frequency axis as a “pseudo-depth”, as is suggested by the above equation. In Figure 2 we show the “pseudo-sections” along the longer horizontal axis X. Reddish color corresponds to resonance peaks, whose amplitude is proportional to red tonality. As can be seen, two resonance surfaces can be distinguished, although not continuous across the whole area and partly overlapping.

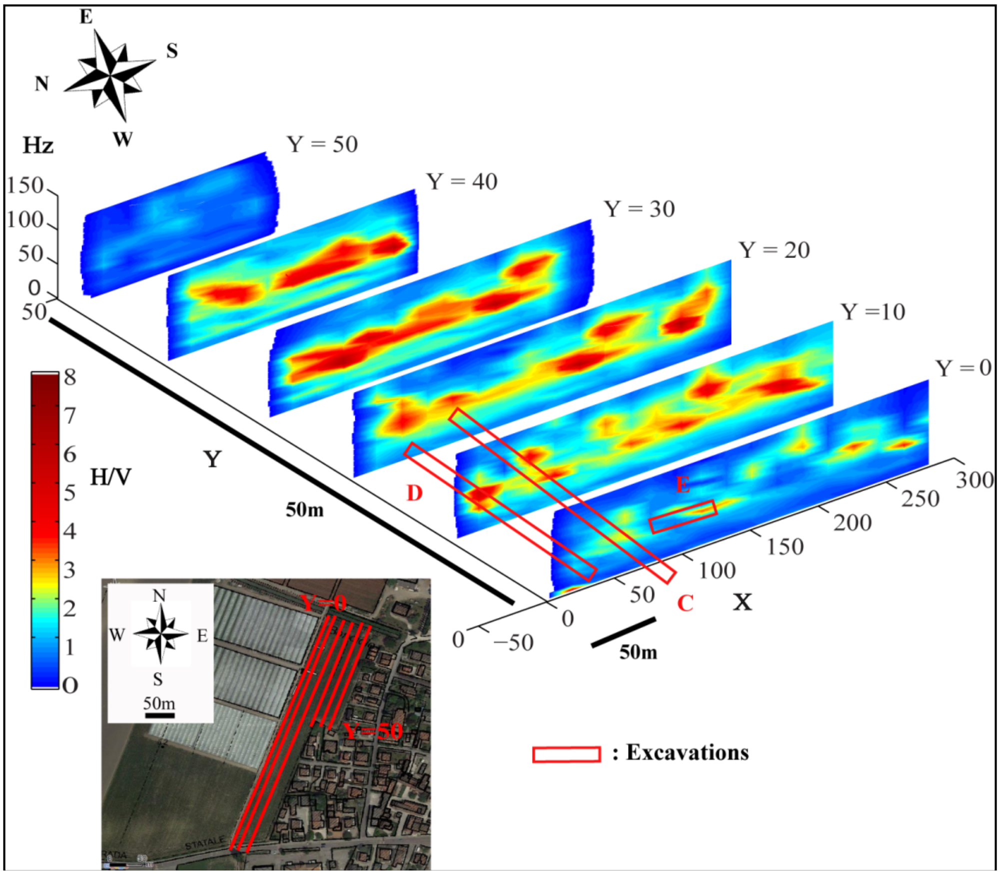

Figure 2 *Profiles of interpolated HVSR curves, along the y axis. The red rectangles highlight the extension of trenches C, D and E.*

After measurements, trench C was re-opened, to verify the geophysical findings of the HVSR survey, and then the above spectral peaks could be assigned to specific paleo-surfaces. Using the approximate formula (Ibs Von Seht and Wohlemberg, 1999):

$$h = \left[\frac{V_S\ (1-x)}{4f_r} + 1\right]^{\frac{1}{1-x}} - 1$$

(f_r is the fundamental resonance frequency) and taking the value of 100 m/s for V_S and 0.44 for exponent x, derived from an available Vs seismic profile in the vicinity of the site, the resonance peaks at 41 Hz and 61 Hz, measured at the HVSR site acquired on trench C, before re-opening, furnished two estimated depths h of respectively 45 and 70 cm b.g.l., in excellent agreement with the archaeological information. As far as the geomorphological environment is concerned, an ERT profile was carried out before re-opening trench C, putting electrodes at 50 cm of distance from each other and obtaining an investigation depth of about 3.5 m. Apparent resistivity data were acquired using the Wenner-Schlumberger array. Induced Polarization (IP) data were acquired as well, bearing in mind that chargeability is independent of resistivity and that fine sediments show a different chargeability, as a function of porosity and clay content (Iliceto *et al*., 1982). The vertical sections of estimated true resistivity and chargeability are shown in Figure 3. The resistivity image shows essentially two-layered sub-surface, although quite inhomogeneous, where the upper layer is more resistive that thickens towards the right (South) end. The discontinuity between the layers has no correlation with the paleo-surfaces. The upper layer is more heterogeneous in correspondence of re-filling of old trenches C and D, as obvious. The chargeability section shows essentially a non-polarizable upper layer, while the second layer is increasingly polarizable towards the right (South) end, while its resistivity remains low. A possible explanation of such behavior resides in the different response of the two investigated properties to the clay content and porosity. In fact, maximum chargeability of fine sediments is shown by the sand-clay mixture, since presence of the clay activates the membrane polarization effect (M.P.E.). Direct information confirms the presence of a paleo-riverbed, characterized by a clayey sand texture, just the combination which gives the maximum M.P.E..

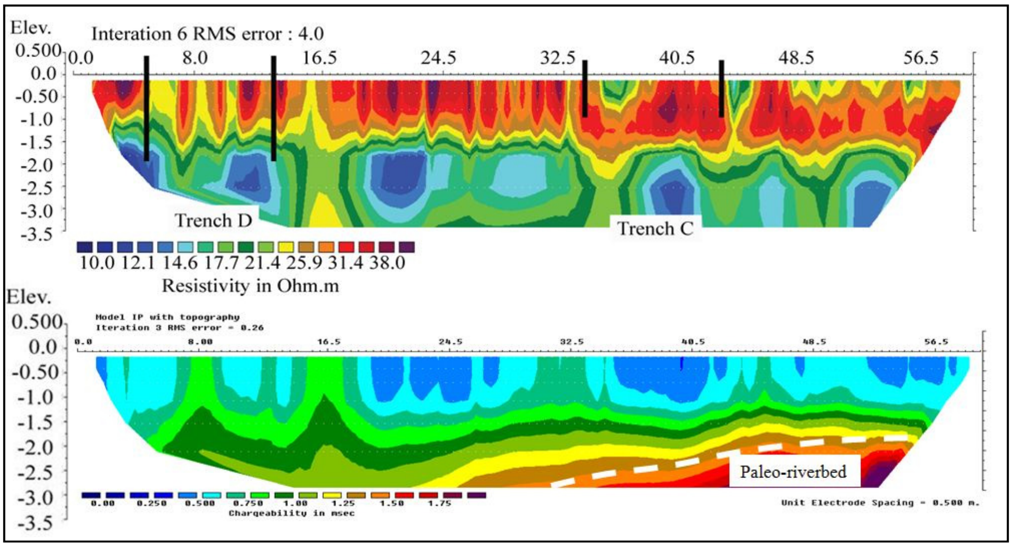

Figure 3 *2D resistivity (above) and chargeability (below) inversion models of the ERT/IPT profile.*

Conclusions

In this paper we showed that, wherever common geophysical methods for archaeology are hampered by urbanization and/or unfavorable subsurface lithologies to detect specific targets, as paleo-surfaces embedded in a conductive clayey lithology, alternative methods, as HVSR, can be advantageously used, bearing in mind that trampling due to human activities could have increased the acoustic impedance of sediments lying below the paleo-surface. Likewise, IP can provide complementary, valuable information about the paleo-geographic environment which indeed aid in the reconstruction of the paleo-geomorphological evolution of such important archaeological sites.

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