The HVSR technique from array data, speeding up mapping of paleo-surfaces and buried remains. The case of the Bronze-Age site of Pilastri (Italy)

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Summary

In the framework of a geophysical survey at the “Pilastri Terramara” Middle Bronze Age archeological site (Northern Italy), which aimed at using cost-effective approaches to investigate a 12.000 m^2 portion of land, we verified that in this site the most commonly used GPR, magnetometry and ERT geophysical methods were hampered by specific unfavorable conditions. Since the main purpose of the survey was to obtain information on ancient walking surfaces, we speculated that compaction, caused by the trampling of human activity over centuries, increased both density and seismic velocity of these paleo-surfaces. Assuming that such compacted layers still lie embedded in the shallow subsurface we successfully used the Horizontal-to-Vertical Spectral Ratio of microtremors, popular as HVSR, as a mapping tool. HVSR technique is seldom used in archaeological studies. The curve obtained by this method shows peaks and features that can be associated to the elastic impedance contrasts of a layered subsurface. Results from a previous single-station HVSR survey carried out on the whole area and consisted of 67 measurement points, allowed to obtain an indication about acoustic impedance contrasts and to spot few anomalies. The preliminary, yet promising result however, needed further acquisitions in order to achieve a better spatial sampling. We then tested microtremors acquisition using a linear array of seismic prospection geophones (4.5 Hz proper frequency) which have a worse response with respect the short period sensor used in single-station configuration. Yet the use of the array allowed for a comparable mapping of both paleo-surfaces and anomalies and data collection was performed at 24 locations simultaneously, so greatly accelerating the field work. In the following the two approaches are compared and an anomaly is highlighted which was located outside the hypothesized Bronze Age settlement area. Once excavated, such feature revealed to be a layer of roman age remains. Further, we show our best GPR section over the same anomaly. An indication was present in the GPR section but this became clear only afterward.

Introduction

The archaeological site of Pilastri is part of the demographic phenomenon of the Middle Bronze Age popular as “terramare” (1700/1650-1350/1300 BC), in the Emilian Po plain (Northern Italy, Figure 1). The typical structure of these settlements was quadrangular in shape, surrounded by a terrigenous embankment and a ditch (Chierici, 1871; Desittere, 1997), and often filled with water taken from a nearby river. Inside, they were artificially flooded and houses were built on a wood platform. The Emilian Plain is composed of a thick sequence of alluvial sediments, mainly clayey-silt and its landscape is characterized by the presence of slightly elevated and elongated features, composed of sand, related to paleo-riverbeds that constituted the ideal place to build the "terramare" settlements and often, in later times, were re-occupied by Romans.

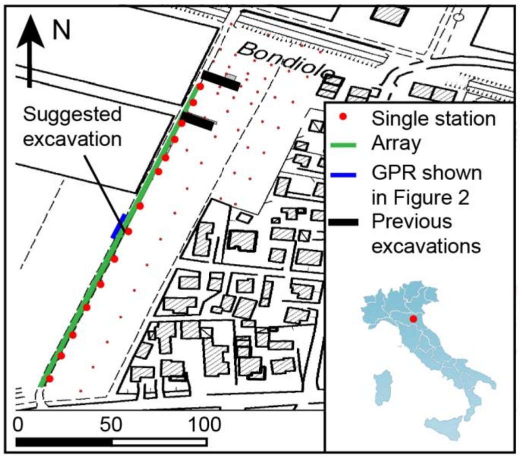

Figure 1: Aerial view and location of the Pilastri arcaeological site.

Recent studies (Nizzo, 2014; Nizzo et al., 2015) hypothesized that the Pilastri settlement could actually extend outside the originally established bordering (Balasso and Michelini, 2013, personal communication). Therefore, the main purpose of the geophysical investigation was to use a cost-effective tool for the recognition and localization of paleo-surfaces beyond the eastern limit of the main settlement, over an area of about 12,000 square meters.

The technologies available to our research group and mostly encountered in archaeological studies are magnetometry, Electrical Resistivity Tomography (ERT), and GPR. Unfortunately however, the Pilastri site lies in part under the iron structure of greenhouse cultivations and is surrounded by houses at the eastern and northern edges. These circumstances made the magnetometry survey useless. Further, the nature of the target we wanted to find, i.e. thin compacted silty-clayey layers embedded in less compacted material of the same lithological nature, makes it difficult to apply the ERT method (Santarato, 2003). Once considered the area to cover, the costs and the working time necessary for the data collection, such a target turns to be well beyond the resolving power of any reasonable choice of electrode spacing. Finally, the prevailing clayey texture of the sediments severely hampered the use of the GPR. Our tests showed that when using a 400 MHz antenna the investigation depth was severely reduced, while using a 100 MHz one resulted in an insufficient resolving power. Besides these difficulties, a proper acquisition of both ERT and GPR data to map such an extended area requires a dense grid of profiles, which would make the survey exceedingly time consuming. Therefore, we decided to test a method which is much more common in geology rather than in archaeology: the HVSR.

The HVSR method is based on the evaluation of the resonance frequencies due to the presence of layers with increasing acoustic impedance. The rationale for using this approach in such a context is primarily the assumption that the paleo-surfaces were stiffened due to trampling of human activity over centuries of occupation. Secondly, HVSR is able to map subsurface elastic variations spanned over short distances (Aki and Richards, 2002, Bignardi et al., 2014, Bignardi et al., 2016), hence allowing capturing such variations by acquiring data over an optimized grid of locations. HVSR applications are scarcely documented in archaeology and few examples exist whose scope is different from the present application, e.g.: Castellaro et al. (2008), Bottari et al. (2012), Wilken et al. (2015), Obradovic et al. (2015). In previous work, Abu Zeid et al. (2016, 2017) showed 2D vertical slices, derived from the 3D volume built by the single-station data as compared with the 2D ERT. In the present work we show a comparison of 2D sections (Figure 2) obtained both from single-station and from an array configuration. Despite the fact that prospection designed geophones (4.5 Hz) were used, which have a worse low frequency response, the array achieved results comparable to those of the single-station. Further, the array approach acquired 24 receivers simultaneously so that the result was achieved 24 times faster and using low-cost equipment.

Furthermore, we show the portion of our best GPR section acquired on this site (Figure 3), which lies exactly over an anomaly that a subsequent excavation proved to be a thin layer of Roman remains, consisting for the most of brick fragments. As it is clear by inspecting the section b) in Figure 2, HVSR was successful in highlighting the buried target, while the GPR result became clear only after the excavation.

The consideration to be made is that HVSR may represent a useful, non-invasive tool for mapping very shallow targets, especially in array configuration, and it is worth to be included as a candidate member of the family of geophysical methods useful in archaeo-geophysics.

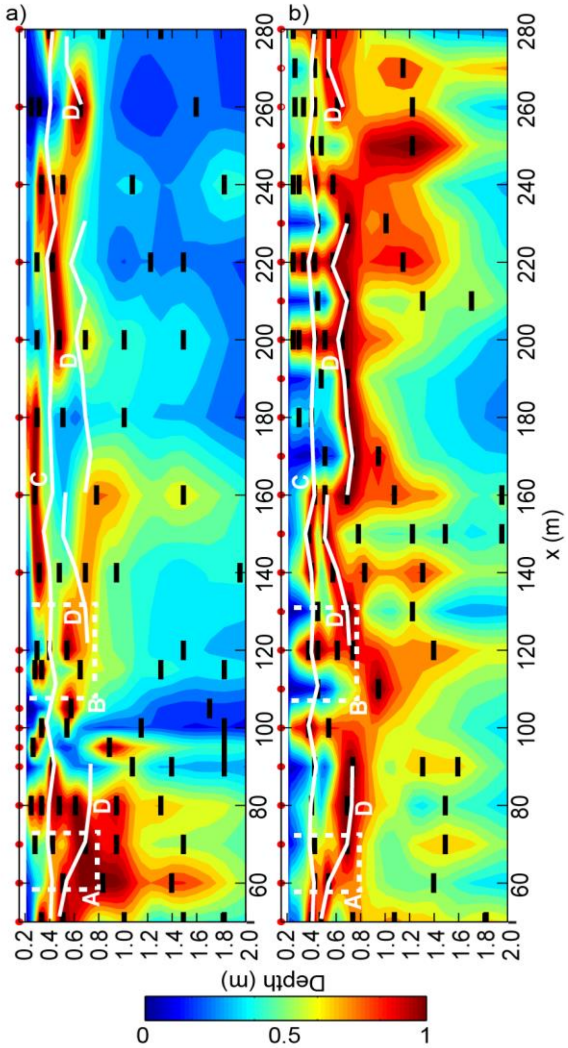

Figure 2: Section obtained by placing normalized HVSR curves side by side. a) section obtained from 22 single-station measurements (Geophone with 2Hz proper frequency). b) section obtained by a measurement comprising the acquisition at 24 geophones (4 Hz proper frequency) simultaneously. HVSR amplitudes are normalized. Label "A" indicates an old, re-filled excavation while "B" highlights the excavation that we suggested, based on these results, where Roman remainings were found (see figure 3). White lines highlight possible paleo-surfaces, while short black lines indicate local maxima of HVSR curves.

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Method

The HVSR method, (Nogoshi and Igarashi, 1971; Nakamura 1989, 2000), is based on the acquisition of the three components of ambient seismic noise that is induced by different sources that can be both natural and human generated. The ratio between the power spectra of the horizontal $H_i(f)$ and vertical $V(f)$ components is calculated by

$$HVSR = \frac{\sqrt{{H_1}^2+{H_2}^2}}{V} \qquad (1)$$

and the peaks of the resulting curve can be directly related to elastic impedance contrasts in the subsurface. Typically, the subsurface is assumed to be well described by a low shear wave velocity (V_S) layer of thickness H, over a fast half space. In such a case the resonance frequencies f_n are known

$$f_n = \frac{V_s}{4H}(2n-1) \qquad n = 1, 2, \dots, \infty \qquad (2)$$

If the soft layer contains minor impedance contrasts, the HVSR curve will show multiple peaks. In the latter case, linking the experimental H/V curves to the layered subsurface requires an inversion algorithm (Castellaro et al., 2005, Herak, 2008; Mantovani et al., 2015; Bignardi et al., 2016).

Here we discuss a 2D section obtained by placing side by side the HVSR curves obtained for a set of aligned locations. In such representation the y-axis is frequency and for sake of interpretation needs to be transformed into depth. Since we are interested in the very shallow subsurface, down to 2 m depth, to translate the frequency axis to a depth, inversion is actually not needed and it is sufficient a simplified approach. Indeed, the site is characterized by a thick sedimentary cover which results in a main resonance peak around 0.8 Hz. This peak dominates over the entire HVSR curve, so that in such a context available inversion algorithms usually give poor results for frequencies higher than 10 Hz, mainly because the inversion would be dominated by the deep subsurface structure. Moreover, because of the weak impedance contrast represented by the wanted paleo-surfaces any inversion procedure would suffer from severe equivalence issues.

Therefore, as the shallow lithology of the site is almost homogeneous with an average V_S of the shallowest layers known by a nearby borehole (30 m deep), we decided to apply the simplified approach proposed by Ibs Von Seht and Wohlemberg (1999), equation 3, which accounts for the increasing of Vs with depth due to the increasing confinement pressure

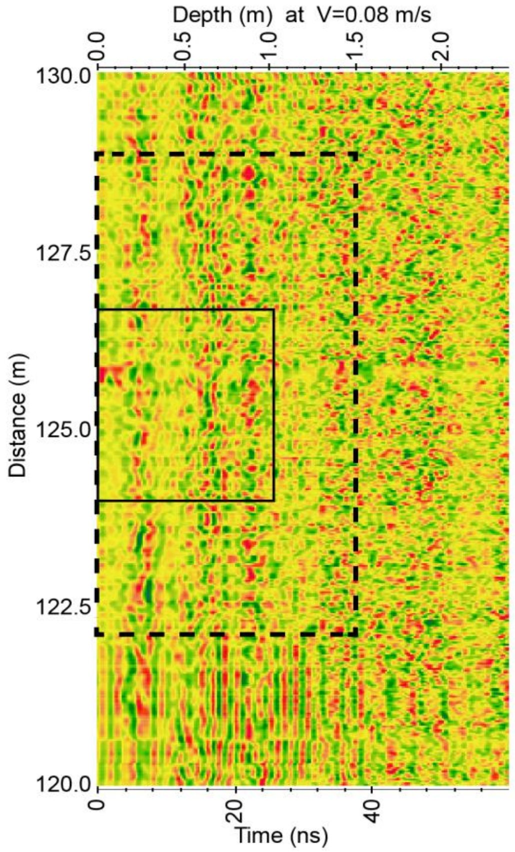

Figure 3: Portion of the GPR survey performed with a 400 MHz antenna before the excavation. A weak anomaly produced by the buried remainings is present, however it could not be spotted on the basis on the lone GPR. Big and small squared highlight the excavation location and the radar signature of the Roman remaining.

$$H = \left[\frac{V_{s0}(1-x)}{4f_r} + 1\right]^{\frac{1}{1-x}} - 1\,, \qquad (3)$$

where f_r is the selected resonance frequency, $x = 0.44$ and $V_{S0} = 100$ m/s. Figure 2a and 2b show the HVSR section built from both single-station and from array measurements respectively. For the single-station measurement 22 curves were merged. The equipment used to acquire the single-station dataset comprised a 3D short-period geophone (2 Hz) connected to a M.A.E. Vibralog data-logger. For the array measurement we used 24 three component geophones (4.5 Hz) connected to a seismograph purposely built by our research group.

Since we were mainly interested in the shallow subsurface which, in turn, involves the investigation of the frequency range above 10 Hz, microtremors recordings 15 minutes long were sufficient. The two acquisitions were performed with different location spacing. Receivers are highlighted by red circles on top of the HVSR sections of figure 2. Further, considerations about the sections indicate that despite the apparent graphical difference they look coherent in their main features. Some differences however, were to some extent expected, basically because of three reasons:

- Difference of receivers employed which have different response both in term of proper frequency and amplitude response.
- Difference in acquisition times. Single station was performed one location at a time, while the array recorded simultaneous signals. Further, the two surveys were performed at different times.
- Stochastic nature of the seismic noise and the consequent different "illumination" of the subsurface.

An anomaly "A" could be recognized as coincident, both in position and depth, with a previously excavated and then re-filled site. Square "B" highlights an anomaly that we suggested to excavate, which turned out to be caused by the presence of a thin layer of Roman earthenware and brick fragments at a depth of 70 cm (Figure 4). White lines drown based on section in figure 2b, and superimposed on both sections, highlight possible surfaces of interest. Surface "C" lying roughly at a depth of 40 cm is most certainly coincident with plough base. Surfaces "D" are probably discontinuous portions of a paleo-surface. They lie at a depth of about 70 cm, the same depth of the discovered Roman remains.

Figure 3 shows a detail (10 meters centered at x=125 m, corresponding to anomaly "B" of figure 2), of the best GPR result we were able to achieve over the same profile using a 400 MHz antenna. The full radargram looks as the shown image for its entire length (280 m). As such no indication was obtainable only on the basis of GPR. In fact, the anomaly signature is very weak so that its presence was identified only after that we knew what to look for. Finally, in figure 4 we show a picture of the open excavation with the Roman remains.

Conclusions

We presented and discussed a successful application of the HVSR geophysical method at the archaeological site of Pilastri (Northern Italy). Geological setting and urbanization conditions of the investigated area do not allow a successful use of the geophysical methods most commonly employed in archaeology. Therefore, we decided to test whether HVSR can be used to gain information about the local subsurface, and in particular, for detecting paleo-surfaces. The hypothesis was that these paleo-surfaces were compacted and stiffened by trampling, so to create an elastic impedance contrast detectable by investigating the HVSR curve at sufficiently high frequencies. Indeed, such paleo-surfaces were found in connection with small local maxima of the curves which in some cases resulted nicely aligned to form smooth surfaces. Further, highlighting in the interpolated sections the depths corresponding to these local maxima allowed following at glance the surfaces. Finally, presence and estimated depth of paleo-surfaces were afterwards confirmed by direct excavations.

Figure 4: Excavation performed after the geophysical survey. A thin layer of Roman remainings was found at the exact place and depth obtained by the HVSR investigation.

We showed that equivalent results may be obtained both using single-station and array configurations. Despite that 4.5 Hz low-cost prospection geophones were used the array performed nicely and allowed recording 24 stations simultaneously, so greatly reducing acquisition times. To the best of our knowledge, this configuration is used for the very first time in archaeological context. The success of this field application shows that the proposed HVSR approach was capable of investigating interfaces of archaeological interest which spread over vast areas, and could be routinely used to pin ancient shallow paleo-surfaces whenever other well-documented geophysical methods can't be used and/or when a low-cost reconnaissance survey is requested.

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Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2017 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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