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The Passive Seismic Technique 'HVSR' as a Reconnaissance Tool for Mapping Paleo-soils: The Case of the *Pilastri* Archaeological Site, Northern Italy

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ABSTRACT Horizontal-to-vertical spectral ratio (HVSR) is a widely used geophysical technique in seismic microzonation studies. It is based on a specific analysis of seismic ambient noise. The method allows to obtain the frequency and amplitude of the resonance peaks of a layered earth with increasing acoustic impedance contrasts. The peaks can be interpreted to obtain an estimation of depth(s) of the impedance contrast horizon(s).

Based on the assumption that long-term human trampling results in sediment's stiffening, which increased both density and velocity of seismic shear waves, the HVSR method was applied to investigate the shallow subsurface of an important, Middle Bronze Age, archaeological site called '*Pilastri* Terramara' discovered at the end of the last century.

Following recent excavations, archaeologists supposed that the settlement could extend outside the initially hypothesized borders, and decided to involve geophysicists to verify the truthiness of this new hypothesis and consequently to map the possible spatial extent of the paleo-surfaces frequented by ancient occupants. The purpose of the geophysical investigation was then to detect and possibly to map one or more anthropogenic paleo-surfaces over a relatively large area (about 12000 m^2).

Unfortunately, direct evidences showed that the paleo-surfaces were embedded in clayey sediments and laying at depths ranging between 50 and 170 cm below ground level. Furthermore, the area to be investigated is occupied by a farm with glasshouses and other buildings. These obstacles constituted a real challenge that hindered the utilization of the most commonly used geophysical methods in archaeology, i.e. ground penetration radar (GPR), magnetometry and electrical resistivity tomography. For these reasons, we decided to use the HVSR method as a reconnaissance exploration tool, to confirm or rule out the presence of such paleo-surfaces.

Spectral peaks related to acoustic horizons provided evidences about their presence and allowed to estimate their depths as was later confirmed by a new excavation. Copyright © 2017 John Wiley & Sons, Ltd.

Key words: Impedance contrast; paleo-archaeological surfaces; *Pilastri* 'Terramara' settlement; pseudo-3D representation; horizontal-to-vertical spectral ratio (HVSR); Nakamura method

Introduction

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 'terramare' in the Emilian Po Plain (north Italy: Figure1). The typical structure of a 'Terramara' settlement is well documented in the literature and is described as quadrangular in shape, surrounded by terrigenous embankment and a ditch (Chierici, 1871; Desittère, 1997), often filled with water taken from a nearby river or stream. Inside, they were

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artificially flooded and houses were built on a wood platform.

The Eastern Po Plain, from now on 'Emilian Plain', where many of such archaeological sites were documented, is composed of a thick sequence of alluvial deposits (see, in general, Castiglioni *et al.*, 1989; Bernabò Brea *et al.*, 1997; and, for a recent geomorphological synthesis limited to the documentation of the provinces of Parma and Piacenza, Boudry, 2015). These are mainly clayey-silt sediments which cover almost completely the north-western portion of the Ferrara province comprising the site itself. The landscape is characterized by the presence of slightly elevated and elongated features, composed of sand, related to paleo-riverbeds (Ferri and Cornacchini, 1995). These raised lands [8 to 10 m above sea level (a.s.l.)] constituted the ideal place to build the 'terramare' settlements, which in later times were re-occupied by Romans, who found such locations attractive because of soil fertility.

Based on recent excavations, performed in a preventive viewpoint after the Emilia earthquake (20 May 2012, Ml 5.9, depth 6.3 km), archaeologists hypothesized that this settlement could actually extend outside the bordering levees previously discovered, and consulted geophysicists for the execution of a cost-effective survey capable of confirming their hypothesis and possibly to map the locations of these paleo-surfaces in a test site (about 12 000 m^2) located a few tens of metres to the east of the 'terramara' main settlement (Figure 1).

It is known that archaeological surveys can be made cost and time effective by taking advantage of the possibilities offered by using geophysical methods, which allow the investigation of small to large sites with the purpose of identifying areas of interest, so helping archaeologists to plan new excavations or to extend/deepen current ones. The success of any geophysical survey depends on the proper choice of the investigation strategy (Di Fiore and Chianese, 2008), as different geophysical techniques map different physical properties and where one technique is successful others may fail (Hesse, 1999; Piro *et al.*, 2000; Garrison, 2013). The geophysical methods commonly encountered in archaeology are magnetometry, ground penetrating radar (GPR), electrical resistivity tomography (ERT) and low-frequency geoelectromagnetic methods (see, e.g. Gaffney and Gater, 2003). These allow to image the sub-superficial distribution of magnetic susceptibility, dielectric permittivity, electrical resistivity and complex conductivity, respectively.

Each of these methods, however, may suffer some limitation of use under peculiar conditions of the site under investigation. The *Pilastri* site, in particular, lies in part under the iron structure of glasshouse cultivations and is surrounded by houses both towards the east and north. These circumstances make, as we verified by a purposely conducted test (not described

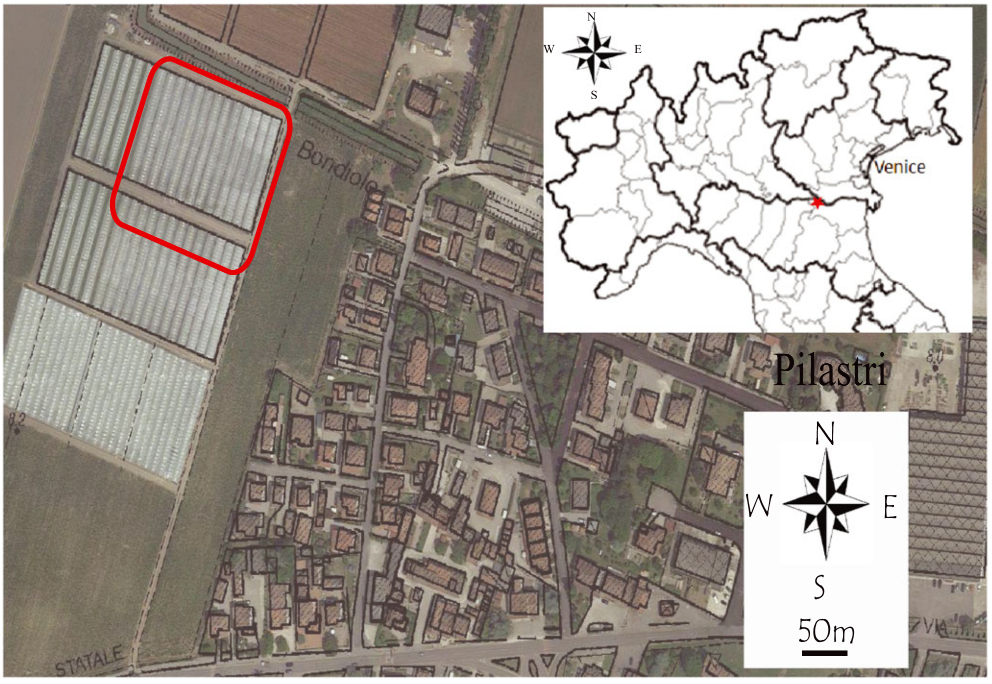

Figure 1. Location map of *Pilastri* Bronze Age site (red star); the red square indicates the part of the site under the greenhouses. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

here), the magnetometric survey pointless. Further, the geological nature of the site makes it difficult to apply the ERT method. In fact, while ERT is successful wherever the paleo-surface separates layers of different texture and composition (see e.g. the 'Isernia La Pineta' – Italy – settlement: Santarato *et al.*, 2001; Santarato, 2003), the paleo-surfaces target of this survey are embedded within the same lithology, which poses severe limitations on the identification of these layers, both because target and surrounding sediments are of similar lithology and of their reduced thickness that is well beyond the resolving power of the method. Nevertheless, for the sake of completeness, we performed an ERT profile, whose meaning is discussed in the second part of this work. Finally, the prevailing clayey texture of the sediments severely hampered the use of the GPR, dramatically reducing its investigation depth with increasing frequency and, conversely, reducing its resolving power with decreasing frequency. A specific test survey (not shown here) was performed using both 100 MHz and 400 MHz antenna, however, the obtained results were useless as the 400 MHz mapped the base of ploughing, while, the 100 MHz provided fuzzy information. Consequently, the only GPR investigation we shall describe is the one conducted on the floor of trench C using a 400 MHz antenna with the purpose of evaluating the thickness of the exposed archaeological remains.

Besides these difficulties, it is worth to recall attention to the fact that a proper acquisition of ERT and GPR data to map a three-dimensional (3D) subsurface should be based on a dense grid of profiles, which would make the survey exceedingly heavy in the field and cumbersome in data processing and visualization for this specific target. Moreover, two or more operators are required for data collection.

The challenges posed by this rather peculiar environment, which is nevertheless quite common in an urbanized, alluvial context, led us to use a method which is much more common in geology rather than in archaeology: the horizontal-to-vertical spectral ratio (HVSR) technique. This method is based on the evaluation of the resonance frequencies due to the presence of layers with increasing acoustic impedance. Therefore, the rationale for using HVSR in a dense acquisition grid at the *Pilastri* site is primarily the assumption that the paleo-surfaces were stiffened due to trampling of human activity over centuries of occupation and secondly, the HVSR is able to map subsurface elastic variations spanned on short distances (Aki and Richards, 2002; Bignardi *et al.*, 2014; Bignardi *et al.*, 2016), hence allowing to capture such variations by acquiring data over a dense grid of points whose dimensions can be regulated in accordance with the hypothesized spatial extent of these paleo-surfaces. Moreover, the HVSR data acquisition technique may be carried out by just one operator. Input data are the recordings of the three Cartesian components of the ambient seismic noise (microtremors) at each grid point location for a few tens of minutes (maximum recorded length of 15 minutes). This method is certainly slow to map in detail the subsurface, if compared with other seismic methods, as P or S seismic tomography, which could be equally suitable to the present issue, although with penalties similar to ERT and GPR methods as mentioned earlier. An additional penalty of using P and S-seismic method regards the anthropogenic noise that surely would reduce the quality of the data.

Bearing in mind the earlier mentioned considerations and for this specific test site, the HVSR method was selected to test its performance as a tool for indirect archaeological investigations as its use is scarcely documented in the literature. We cite, among few others, Castellaro *et al.* (2008), who used the method together with GPR to investigate the subsurface of a Roman Amphitheatre in an urban context to a few tens of metres. However, the authors estimated the possible depths of impedance contrasts mainly to characterize the seismic response of the site, rather than to map paleo-surfaces of archaeological interest. Bottari *et al.* (2012), used HVSR and GPR to locate an ancient buried harbour. Recently, a similar seismic method was used to retrieve very shallow archaeological information by Wilken *et al.* (2015). Their approach, however, was tested to retrieve the location of buried houses (i.e. localized acoustic impedance anomalies) made in bricks and so presenting marked differences in acoustic impedance much greater than those assumed for the *Pilastri* case. Further, they used surface waves produced by an artificial source rather than ambient microtremors. Their approach, however, requires specialized professionals (i.e. applied geophysicists) for data collection, processing and interpretation.

The aim of this study is to show that HVSR is a useful, non-invasive tool for mapping very shallow targets and, in the authors opinion, is worth being included as a candidate member of the family of geophysical methods useful in archaeo-geophysics discipline.

The *Pilastri* site

The discovery of the *Pilastri* site dates back to the end of the 1970s of the last century, when Gianfranco Po, a local passionate, reported the emergence of artefacts

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which turned out to belong to the Bronze age. Between 1989 and 1995 a series of extensive archaeological investigations were undertaken (Desantis and Steffè, 1995), which allowed defining the extent of the main settlement, quadrangular in shape, covering an area of about 11 000 m^2 (red rectangle, Figure 1). The research in *Pilastri* was resumed in 2012 after the Emilia earthquake sequence when a new portion was discovered 250 m to the east of the main site following construction works of a new primary school to substitute the one damaged during the earthquake (Nizzo, 2014; Nizzo *et al.*, 2015). As of 2013, five archaeological excavations (A, B, C, D, E, see Figure 2) were carried out to further characterize the settlement, whose extent and state of preservation had been only hypothesized in the previous campaign. Trenches B and C confirmed the presence of frequentation levels of the Bronze Age, highlighting a proto-surface at a depth varying between 70 to 40 cm below ground level (b.g.l.). This surface was found only for a certain length of the trenches while it disappears moving both to the west in trench B and to the east in trench C, giving place to Roman age levels. Both horizons extend in the east–west direction over a width of about 100 m. Beyond these limits, the settlement is bordered towards the west by a series of floods that fill a natural depression, while to the east clay sediments prevail, sometimes interrupted by silty sand sediments belonging to a paleo-riverbed of modest extension, with strong presence of large tiles and brick fragments belonging to the Roman period, possibly filling the depression around the settlement (Balasso and Michelini, 2013).

Excavation D, which sampled the external part of the settlement, highlighted the strong impact of the Roman presence, characterized by a scatter of brick fragments, probably used as foundation for walls or to accommodate roads in a farming context. In this regard, the existence of a Roman level defined as stratigraphic unit 4 (SU4), about 180 cm b.g.l.: see picture in Figure 2), located below the level associated to the occupation phase of the Bronze Age, is of particular interest and probably denotes the insistence of a depression beyond the eastern border of the Bronze Age settlement. This would point toward the hypothesis of the presence of a lapped perimeter ditch successively filled during the Roman and post-Roman ages. Silty sand alluvial sediments were found off the western border of the area (trench A), confirming a series of diffuse floods surrounding the prehistoric village. We can then assume the presence of a settlement placed most probably on a natural hill and later reinforced by embankments.

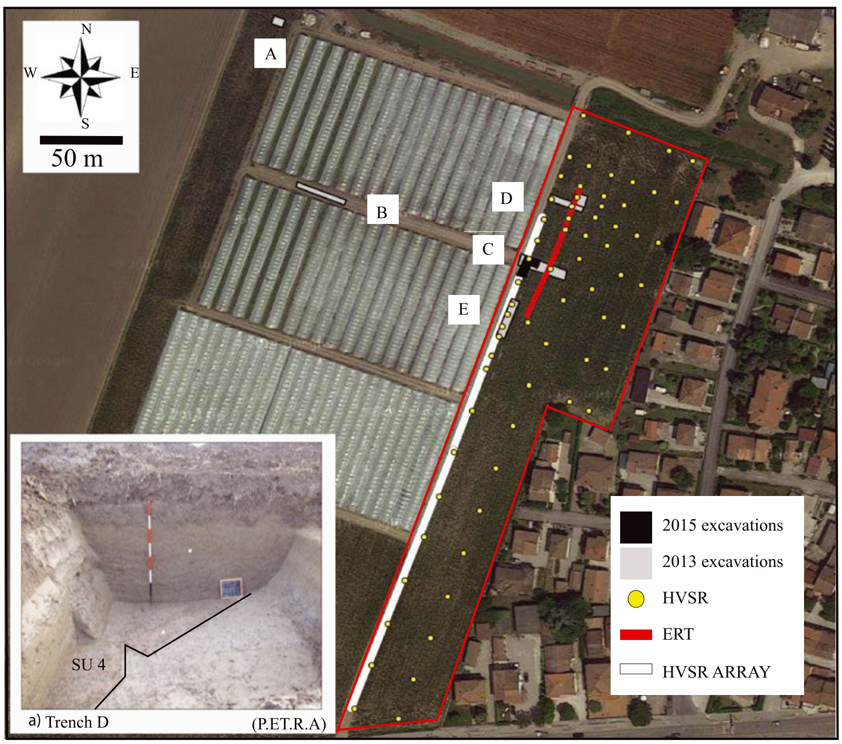

Figure 2. Location of geophysical surveys and of the 2013/2015 archaeological excavations. On the left (box a) details of the Roman level (SU 4) at depth of 180 cm below the ground level are shown. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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Finally, because a paleo-soil of Roman age was detected in trenches C, D and E showing a possible extension of the archaeological area towards the east, it became of utmost relevance to explore the eastern portion of the settlement. Consequently, our attention focused on this area, highlighted by a red rectangle in Figure 2, which extends over 12 000 m^2.

Methods and measurements

HVSR

While the GPR and ERT methods are well established in the archaeological context and thus well-known to the reader, let us recall some concepts about the HVSR method, which the reader could be less acquainted with, together with the description of its specific use in the present work.

The HVSR or 'H/V' method, introduced by Nogoshi and Igarashi (1971) and Nakamura (1989, 2000), is based on the acquisition of the ambient seismic noise (microtremors), induced by natural phenomena (wind, oceanic waves, etc.) and human activities, mainly the traffic of cars and trains. By measuring the three Cartesian components of the particles motion and calculating the ratio between the power spectra of the horizontal (H) over vertical (V) components, above a stack of soil layers of increasing acoustic impedance (i.e. the product between density and velocity V_S of seismic shear waves), the peaks of resonance frequencies are obtained. If the subsurface is simple, i.e. consisting of an homogeneous elastic and soft cover of thickness 'h' resting on a hard substratum, a direct link between the resonance frequencies f_n and the parameters h and V_S of the layer can be found as expressed in Equation 1 (Nakamura, 1989):

$$f_n = \frac{V_s(2n-1)}{4h}, \quad n = 1, 2 \ldots \infty \tag{1}$$

Usually only the fundamental harmonic f_0 is clearly seen, while the upper harmonics can be distinguished only in specific cases of very high impedance contrast. If more impedance contrasts are present, the HVSR curve will show as many peaks, whose amplitude is linked to the corresponding impedance contrast. In the latter case, linking the experimental HVSR curves to the layered subsurface requires a modelling algorithm (Tsai and Housner, 1970; Sánchez-Sesma *et al.*, 2011; Lunedei and Albarello, 2010, 2015), to predict the elastic propagation of waves in the subsurface, coupled with an inversion algorithm of the HVSR curves (Castellaro *et al.*, 2005; Herak, 2008; Priolo *et al.*, 2012; Abu-Zeid *et al.*, 2014; Mantovani *et al.*, 2015; Bignardi *et al.*, 2016). The mathematical treatment of the data is facilitated by the availability of open-source and user-friendly codes.

The equipment adopted for data acquisition is a three-component seismometer (proper frequency 2 Hz) connected to a 24-bit digital seismograph, model Vibralog (M.A.E.s.r.l., Italy, www.mae-srl.it/prodotti/showprodotto/43). A total of 67 measurements were performed with this equipment (Figure 2, yellow points) on the eastern side of the *Pilastri* terramara settlement. All recordings lasted 15 minutes, since we were mainly interested in the shallow subsurface which, in turn, involves the investigation of the frequency range above 10 Hz. The measurements were acquired on a regular grid of 20 m, which was locally tightened to 10 m and 5 m over the 2013 excavations to increase the lateral resolution over the most interesting area. The acquired data were processed using the open software Geopsy (www.geopsy.org). Nakamura's approach requires that the seismic ambient noise field should be homogeneous across all azimuths; therefore, the directionality of the noise fields was analysed first, to reject anomalous data. All datasets were evaluated as free of such trouble and the HVSR curves as a function of frequency f were calculated using Equation 2:

$$HVSR = \frac{\sqrt{|X(f)|^2 + |Y(f)|^2}}{|Z(f)|}, \tag{2}$$

where Z(f) and X(f), Y(f) are the frequency spectra of the vertical component and the horizontal, orthogonal components, respectively. In Figure 4 we report the HVSR average curves of four stations (10, 11, 12 and 14) acquired in and around the site of trench C. Note that the spectral maxima are centred at frequencies greater than 30 Hz. Hypothesizing a V_S around 100 m/s, and using Equation 1, the depths to the impedance contrasts are of the order of 1 m or less, i.e. the possible depth(s) of the paleo-surface(s).

Usually, the depth of a seismic impedance contrasts (i.e. discontinuity or physical surface) is retrieved by an inversion procedure, as explained earlier. Unfortunately, available inversion algorithms give poor results for frequencies higher than 10 Hz, because the inversion would be dominated by the seismic signature of deep features below the measuring point: this can be easily verified by performing a few tests with the popular, free inversion codes (Herak, 2008; Bignardi et al., 2016). Moreover, any inversion procedure is inherently ambiguous, because of the ratio present in the right term of Equation 1, so that a strong equivalence issue may arise.

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Alternatively, bearing in mind that the shallow lithology of the site is almost homogeneous, and that the V_S values of the shallowest layers were known by independent, previously performed measurements in a nearby borehole to a depth of 30 m b.g.l., a simplified, although efficient, approach was adopted to estimate the depth h to the impedance contrasts, based on the equation proposed by Ibs Von Seht and Wohlenberg, (1999):

$$h = \left[\frac{V_{S0}\ (1-x)}{4f_r} + 1\right]^{\frac{1}{1-x}} - 1 \qquad (3)$$

where f_r is the selected resonance frequency; V_{S0} and exponent x can assume indicative values depending on the texture and composition of the soft cover: for a loose, clayey cover a value 0.44 for the exponent 'x' which controls the increment of the Vs with depth is suggested, while the value of 100 m/s was assigned to V_{S0}. Further, the use of Equation 3 also allowed obtaining different depths whenever multiple resonance peaks were present in the HVSR average curve.

ERT

The georesistivity-meter model SAS4000/ES464 by ABEM Inc. (Sundbyberg, Sweden) was used to collect the data. A profile of 59.5 m was sampled at 0.5 m spacing between contiguous electrodes, using the Wenner–Schlumberger array (Figure 2). An investigation depth of about 3.5 m was achieved along the whole profile, which should be sufficient to investigate the volumes containing the paleo-soils and to shed some light on the underlying geology. Apparent resistivity data were inverted using the Res2dinv program (http://www.geotomosoft.com/), which performs a non-linear inversion of the data based on the Gauss–Newton method (Loke and Barker, 1996), regularized by using the minimum roughness constrain (Occam's inversion: Constable *et al.*, 1987).

GPR

The GPR measurements were performed using the model RIS Plus equipment by IDS S.p.A. (Pisa, Italy). As discussed earlier in the Introduction, we show here only the GPR data acquired with a 400 MHz antenna on the floor of trench C, re-opened in 2015, with the aim to map a dipping horizon discovered to be made of bricks. To this end, three parallel profiles were carried out (yellow lines, numbered 1–3, Figure 3).

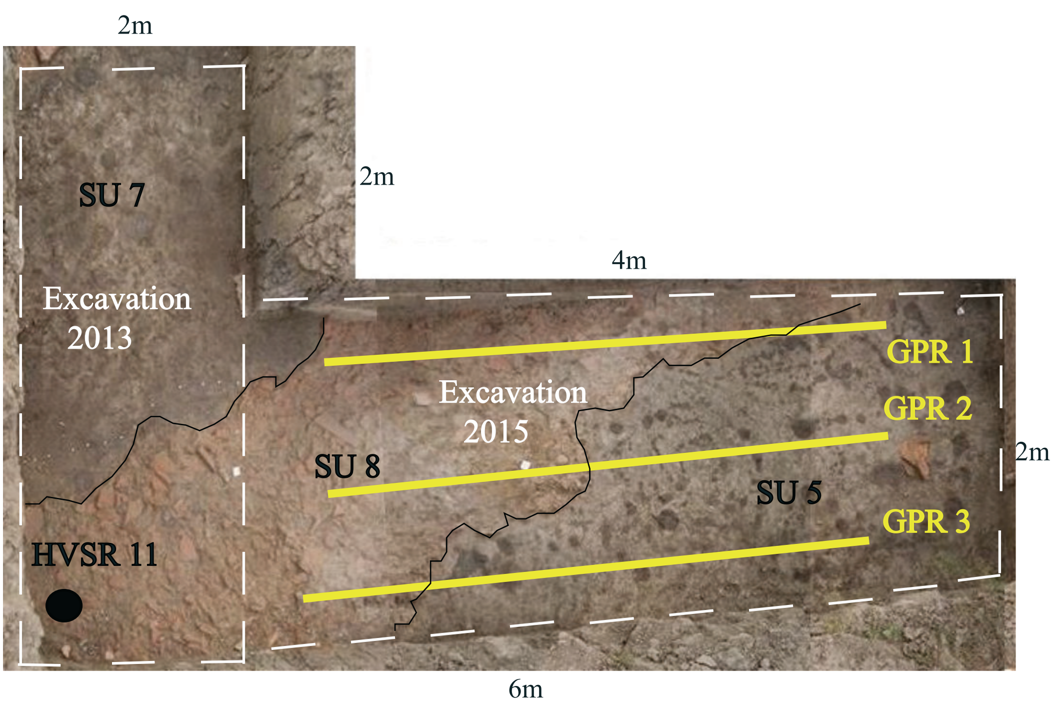

Figure 3. Detail of trench C. where the concentration of material stretching along the portion brought to light in 2015 is shown. Trench borders and stratigraphic units (SUs) are highlighted. SU5: grey silty layer. SU8: stratigraphic unit containing the roman bricks. SU5 and SU7: dark silty-clay layers probably of Roman age (further analyses are needed). Yellow lines: 400 MHz GPR profile. Solid black circle: location of HVSR 11 before the re-opening and extension of the excavation. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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Results and discussion

HVSR

As mentioned earlier, for archaeological purposes we are interested in the high frequency portion of the HVSR curve, which is related to the elastic properties of the shallowest layers.

Therefore, the recorded seismic noise at each location was elaborated, using the software Geopsy, splitting the noise time series in 30 seconds long windows, to select the windows free from strong, transient signals and to compute the final HVSR curve. A 5% cosine tapering was applied to each time-window and the spectra were smoothed using a Konno–Ohmachi algorithm with constant b = 40 (Konno and Ohmachi, 1998). The examination of the HVSR curves showed the presence of several, possibly interesting frequency peaks each one potentially could be related to a probable paleo-surface (Figure 4).

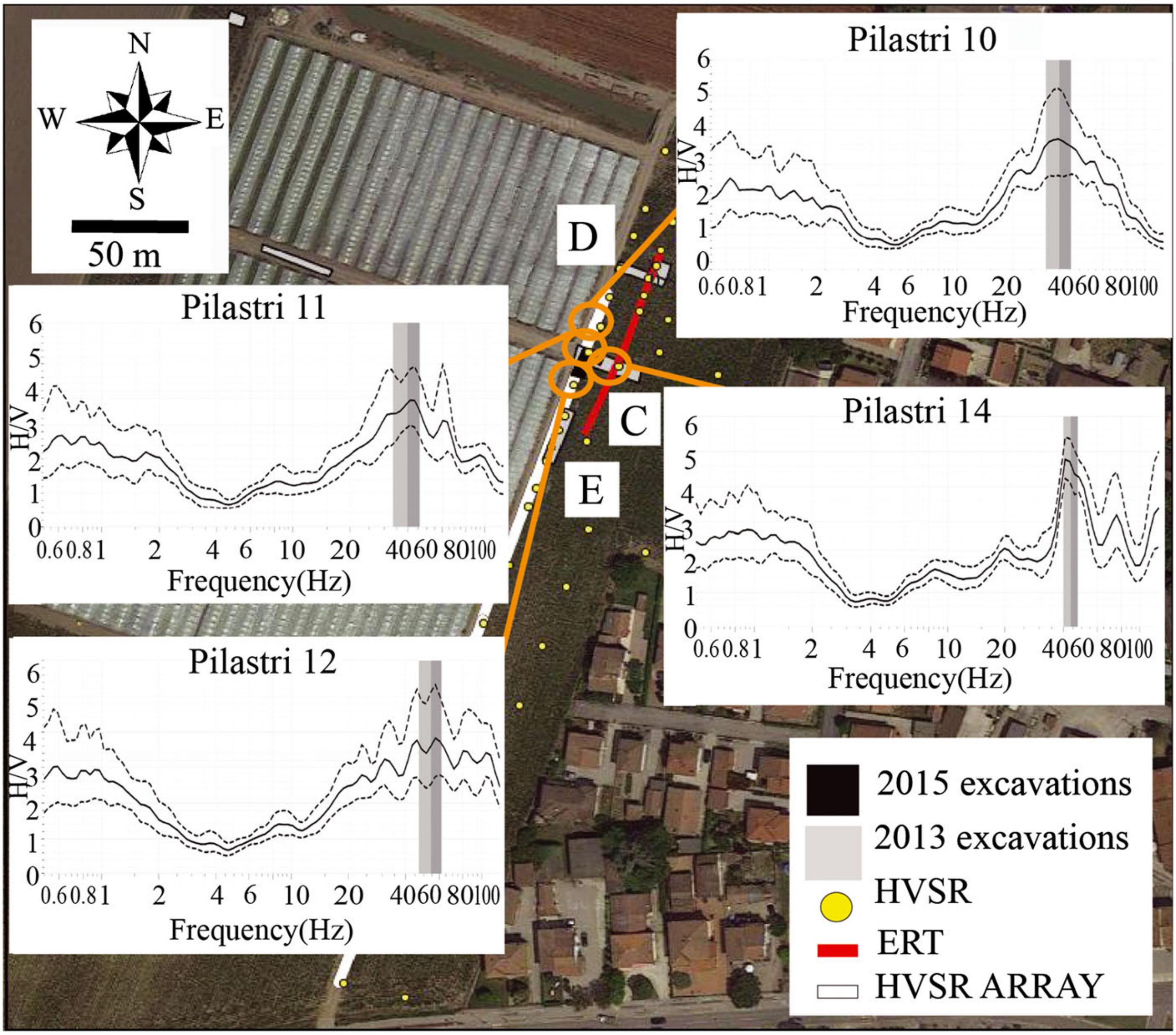

Figure 4. HVSR values obtained at sites 10, 11, 12, and 14 carried out before the start of the partial re-excavation and enlargement of trench C. Site 11 is located in correspondence to trench C (see Figure 3). Sites 10 and 12 are 10 m away towards the northeast and southwest, respectively. Site 14 is located directly over the 2013 trench C. Resonance frequency peaks are highlighted by the vertical grey bars. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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To gain a broader understanding of the spatial distribution of the resonance peaks over the investigated area, we transformed the point-wise spectra into a pseudo-3D view of the HVSR results, where *X* and *Y* axis are the spatial coordinates along the survey, while the *Z* axis represents the frequency. This was done by interpolating the spectra in the space between measurements, so transforming the HVSR curves into volumetric information. In this representation, however, the paleo-surfaces are represented as wide coloured regions. Since the frequency is inversely proportional to the depth of the impedance contrast discontinuity (see Equations 1 and 3), this view is a simple yet efficient tool to represent the informative content of the data.

Examining Figures 5 and 6, we observe that the resonance peaks are sometimes superimposed and sometimes well separated or tend to get confused. We note as well, especially in sections *X* = 160 and *X* = 180, an interpolation effect, due to the spatial sampling, being locally too wide. This means that when we try to represent every discontinuity surface with its resonance

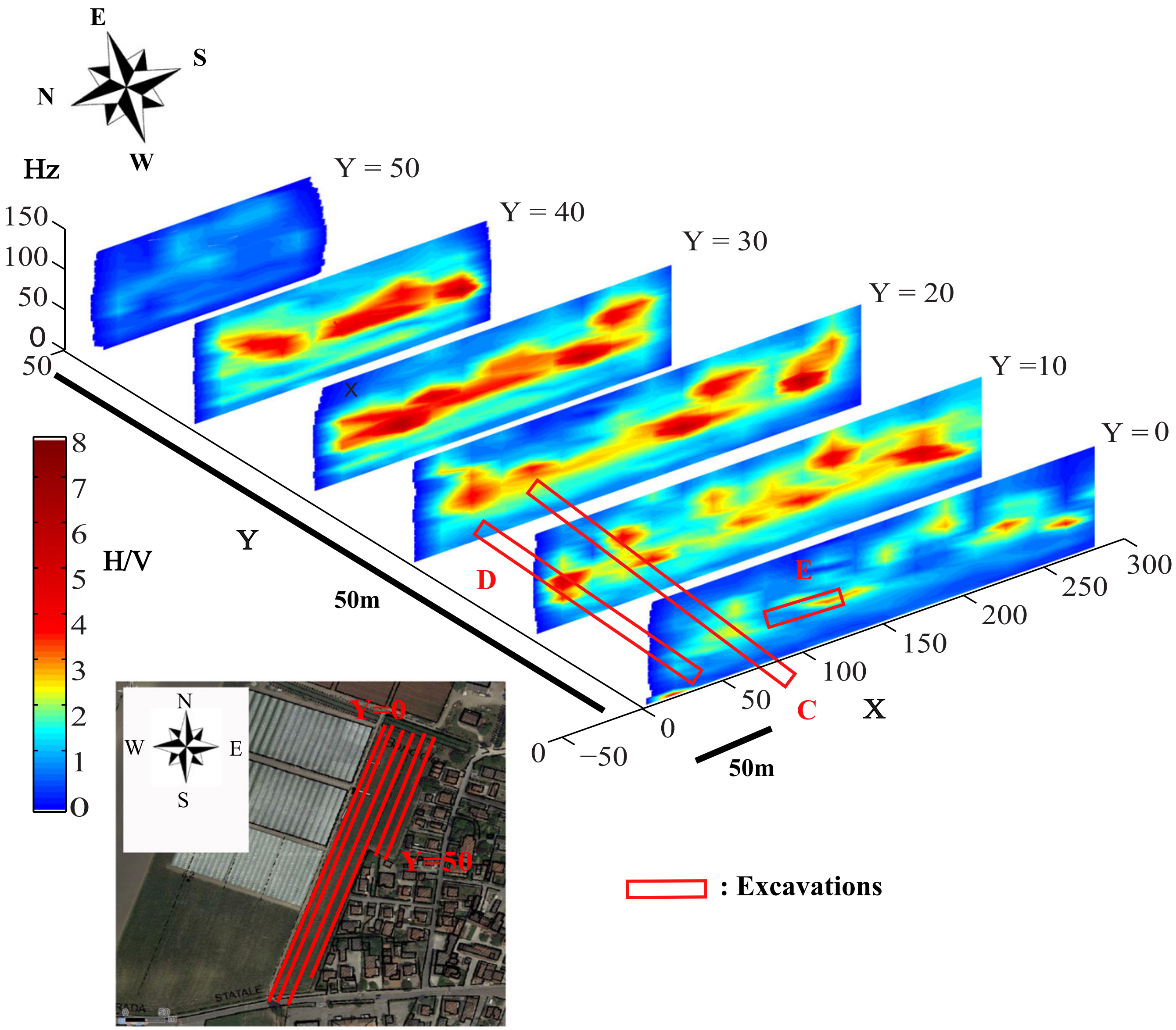

Figure 5. Pseudo-3D representation of the interpolated HVSR amplitudes as a function of space and frequency. The *Y*-axis is oriented towards east–west. Sections are spaced 10 m. The red rectangles highlight the acoustic impedance contrasts related to discontinuities produced by previous excavations and successive filling of trenches C, D and E carried out in 2013. Note that trench C was re-opened in 2015 to identify the encountered impedance anomalies in the same area (see text). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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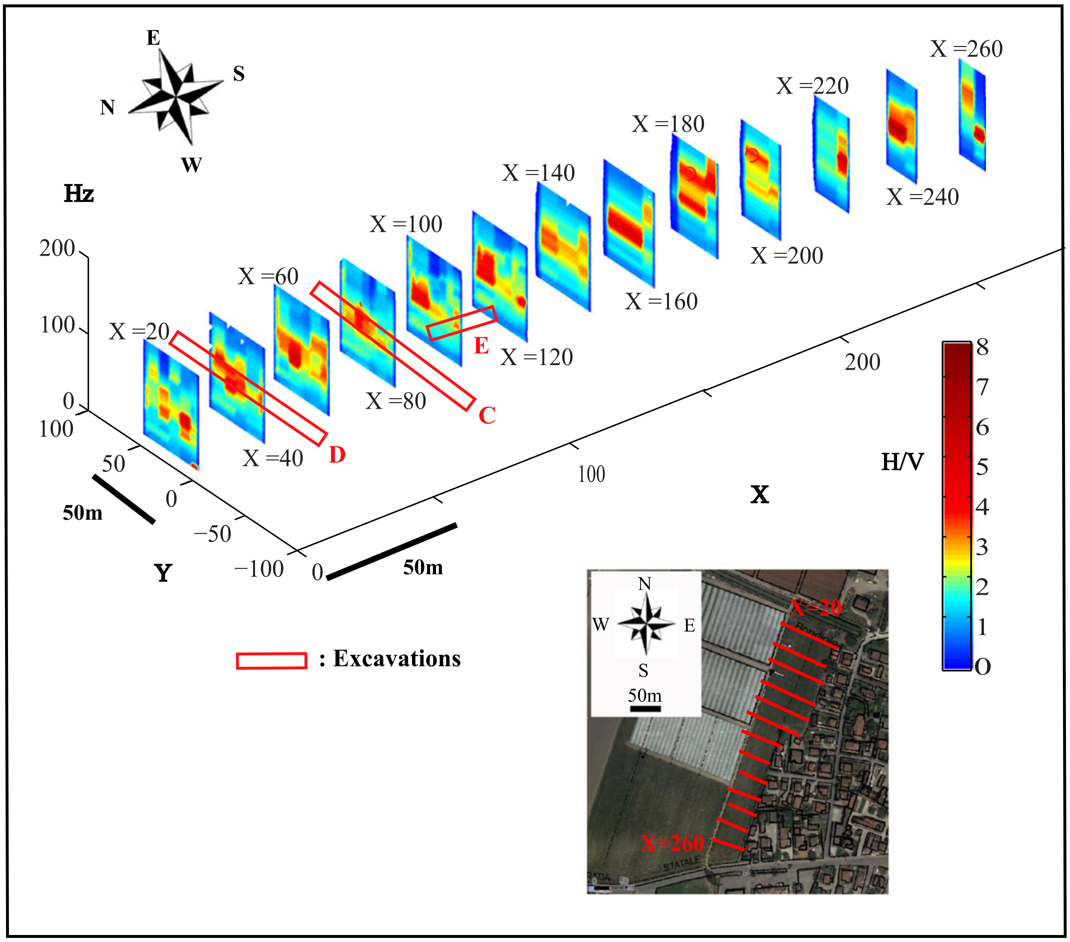

Figure 6. Pseudo-3D representation of the interpolated HVSR amplitudes as a function of space and frequency. The *X*-axis is oriented towards north–south. Sections are spaced 20 m. The red rectangles highlight the acoustic impedance contrasts related to discontinuities produced by previous excavations and successive filling of trenches C, D and E carried out in 2013. Note that trench C was re-opened in 2015 to identify the encountered impedance anomalies in the same area (see text). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

frequency peak, the vertical resolving power (the ability to distinguish overlapping discontinuity surfaces) is limited and leads to mixing of information. If, as hypothesized, the resonances were actually linked to the paleo-surfaces, the lateral variation of amplitude and frequency of resonance peaks may be due to varying degrees of compaction, related to the different use of the area, such as internal communication, housing, road/trail unfrequented areas. Moreover, in the excavated areas, the paleo-soils are laid at different depths, so we did not worry about the oscillations. We remark that we purposely chose to draw only vertical sections. In fact, drawing 3D maps would have implied to associate, in some arbitrary way, resonance peaks (and impedance contrast surfaces) pertaining to different HVSR spectra, to image at least two paleo-surfaces, whose archaeological significance is not within the scope of the present work.

In Table 1 we report as examples the resonance frequencies detected at the measuring sites 10, 11, 12 and 14, together with their respective estimated depths using Equation 3.

The excavation campaign at trench C, completed in October 2015, revealed the presence of a layer of roman bricks with preferential orientation northwest–southeast (Figure 7) lying at about 70 cm depth. HVSR 11, performed above trench C before its excavation, showed two resonance frequency peaks at 40.8 Hz and 61.2 Hz, which resulted in corresponding depth estimate of 70 cm and 44 cm, respectively: the former is consistent with the excavated depth findings consisting of elongated structure composed of Roman compacted bricks while the latter corresponds to the upper paleo-surface, found at that depth during the 2013 archaeological campaign, locally disturbed by ploughing (Balasso and Michelini, 2013).

Table 1. List of resonance frequencies and estimated depths at HVSR sites 10, 11, 12 and 14.

HVSRmeasuring point	V_{S0} (m/s)	HVSR amplitude	Frequency (*f*) (Hz)	Depth (*h*) (m)
10	100	2.88	20.8	1.50
10	100	3.67	35.5	0.81
10	100	3.14	54.4	0.50
10	100	3.46	42.5	0.66
11	100	4.02	40.8	0.69
11	100	3.02	61.2	0.44
12	100	2.54	23.5	1.30
12	100	3.38	30.7	0.95
12	100	4.05	45.8	0.61
14	100	2.26	20.2	1.56
14	100	4.83	42.2	0.67
14	100	3.41	74.0	0.36

Note: V_{S0}, shear wave velocity of the superficial sediments.

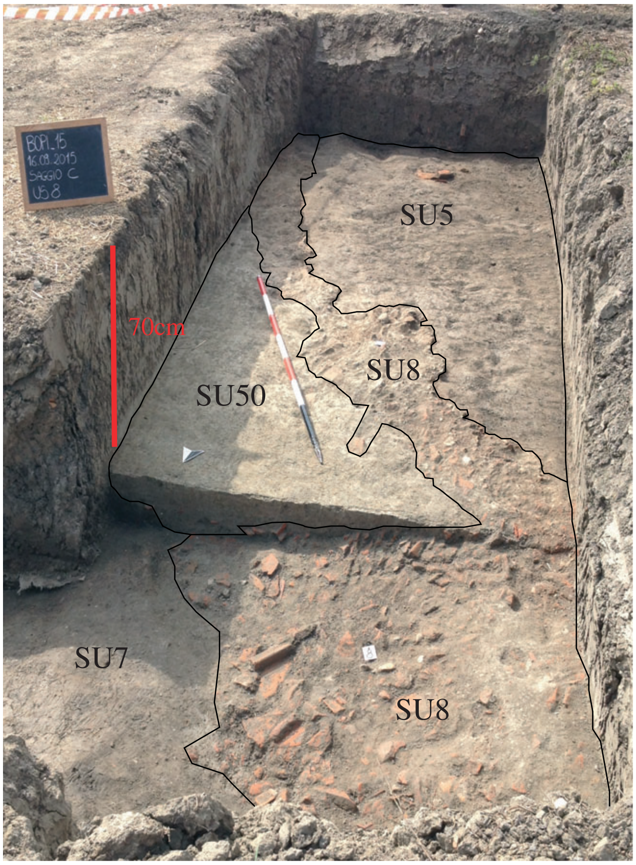

Figure 7. Trench C first opened in 2013 and then re-opened and widened in 2015. It shows the outcrop of bricks (SU8) separating a top cover layer of grey silt texture from a deep dark silty-clay layer. Depth of the finds and stratigraphic units are highlighted. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

In the adjacent measures there are fluctuations of values, probably indicating a variation of the depth of these paleo-surfaces.

Focusing on the frequency sections that can be plotted at and around trench C (Figure 8), we see that the anomaly arising from impedance contrast extends, probably, for more than 10 m, with undulations between abscissae 105 m to 135 m (black rectangle, Figure 8b).

If this is the case we will need in future a denser spatial sampling with respect to the one used in this preliminary study. This in particular would be advisable in order to obtain a more detailed picture of long-term frequentation of the area. For this reason, a second stage of HVSR measures is planned to be conducted in the next future, where sampling will be reduced to 10 m or, locally, even to 5 m and it will be discussed in a future work. In view of such more demanding campaign of measurements, we tested a new piece of equipment capable of performing synchronous multi-station HVSR acquisition. The test was performed along the profile indicated by a white line in Figure 2, with a distance of 10 m between stations. Measurements were executed along two consecutive profiles, each composed of 12 commercial, low-cost three-components geophones (model Mark Products LB15-3D), with 4.5 Hz proper frequency, connected to a 48-channel seismograph, designed and assembled at the Geophysics Laboratory at the University of Ferrara. The results are shown in Figure 9. It is worth mentioning that the anomaly located at $X = 125$ m was found to be caused by the presence of a 5 m × 5 m layer of Roman Age bricks (picture on the right side of Figure 9).

Although these geophones have a much smaller amplitude response (about 78.7 V/(m/s) against 36 V/(m/s) of the earlier-described 2 Hz seismometer, by comparing the profile shown in Figure 9 and profile $Y = 0$ shown in Figure 5 we see that the synchronous multi-station array gives frequencies associated to the impedance contrasts in agreement with the single station data, although amplitudes are different to some extent. We recall that some differences in amplitudes at the frequency peaks among datasets acquired in different times are inherent to the stochastic nature of the signal being processed in the HVSR method. The latter configuration will then be used in the future to speed up field data acquisition.

ERT

The resistivity section obtained by the ERT profile shows an essentially two-layer subsurface, although quite inhomogeneous (Figure 10). Higher resistivity areas (reddish colour) are concentrated in the shallowest subsurface that overlies a more, slightly

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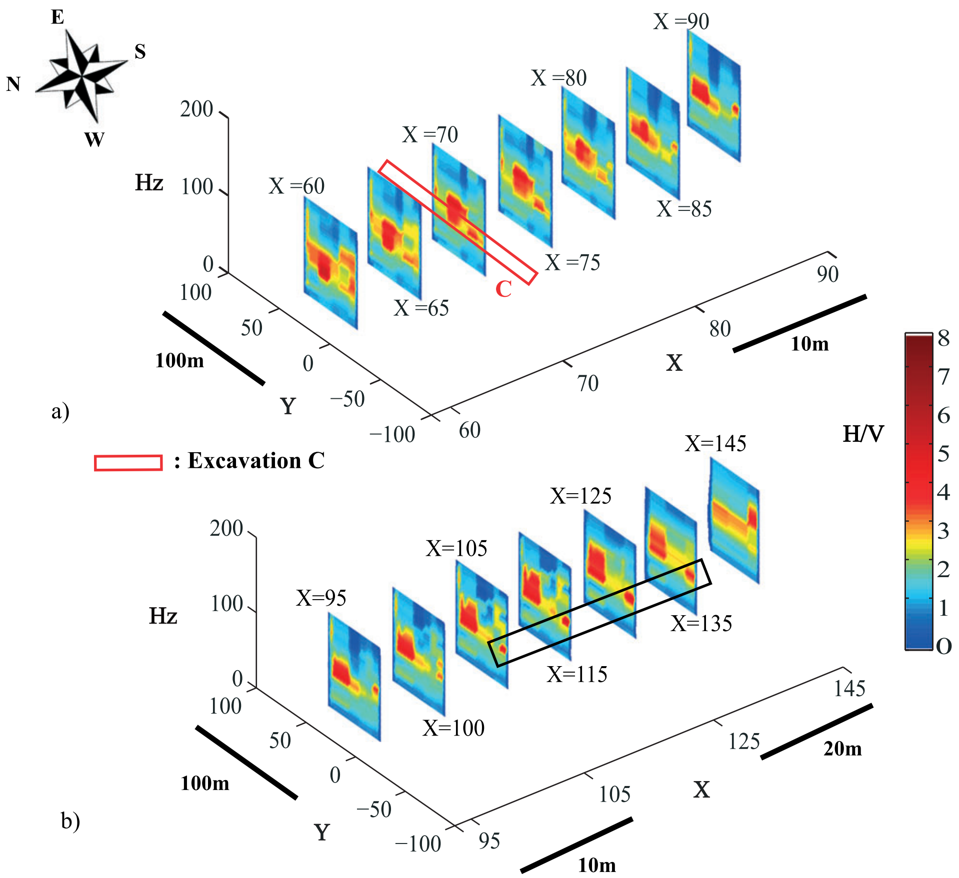

Figure 8. Pseudo-3D representation of the interpolated HVSR amplitudes as a function of space and frequency. The *X*-axis is oriented towards north–south. Sections are 5 m spaced. HVSR amplitude peaks highlighted in red are related to the paleo-surfaces found in trench C.

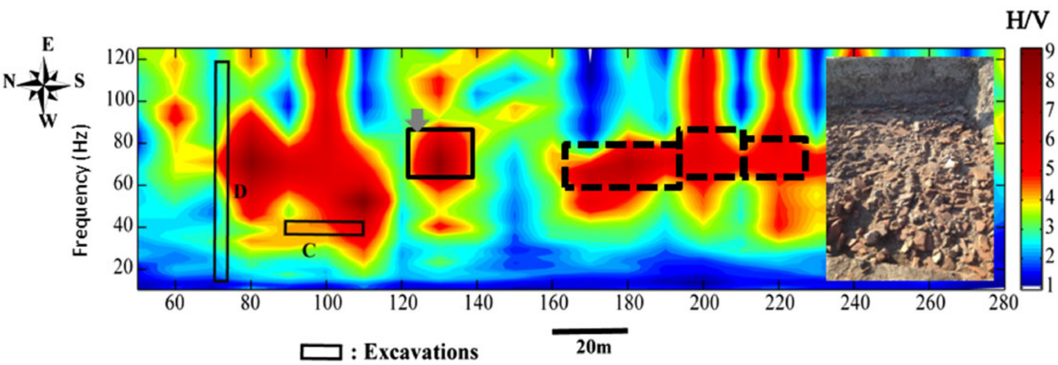

Figure 9. Two-dimensional (2D) section obtained by interpolating the multi-station HVSR amplitudes as a function of space and frequency. Sampling density was 10 m (for location see the white line in Figure 2). Note the correspondence between anomalies and trench locations (C and D). The big arrow indicates the position of the excavation concluded during the revision of the paper. The picture on the right side of the figure shows the Roman Age brick level findings. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

articulated, conductive substratum. The thickness of the resistive layer increases, although irregularly, from about 1 m on the left side (northeast) to about 1.70 m towards the southwest (i.e. right side). Shallow more conductive anomalies interrupt the upper layer at 8 and 16.5 m as well as between 38 and 41 m, i.e. they occur in correspondence of trenches C and D. These variations are associated to the re-filling of the trench after the end of the excavation campaign carried out in 2013. If we look at the depth of the transition we can notice that it reaches about 1 m at trench D, but the layer of archaeological interest was found at 1.8 m at

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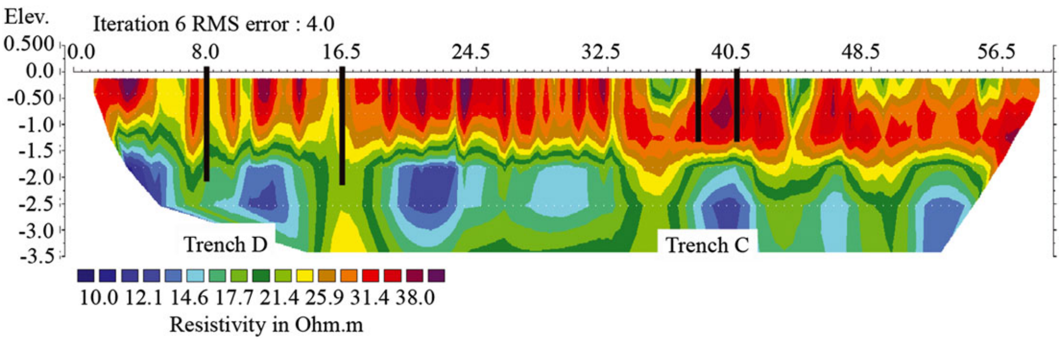

Figure 10. Two-dimensional (2D) inversion resistivity model. Vertical lines: limits of trenches C and D. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

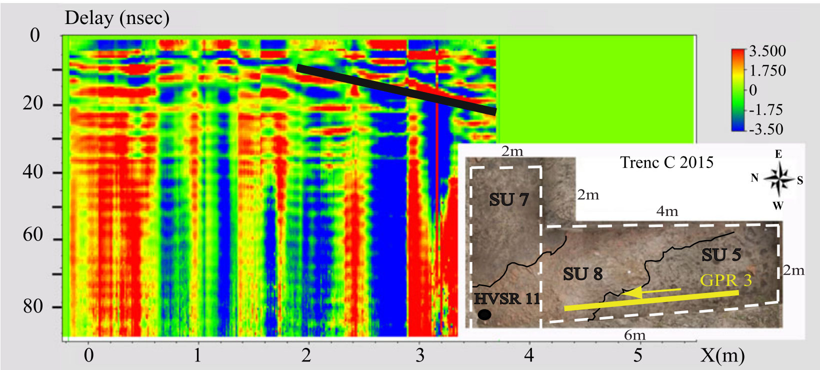

Figure 11. Radargram section No. 3 conducted on the floor of trench C. Thick black line: reflection pertaining to the dipping morphology of the brick layer. Box on the right shows an aerial view of the trench as well as its location. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

this location, so this discontinuity cannot be associated to the presence of an anthropogenic paleo-surface.

GPR

The survey conducted on the floor of trench C (Figure 3), detected a dipping left to right reflection surface (Figure 11). During data collection, at about 2.5 m from the beginning of profile, bricks were barely visible and their farther extension was hypothesized by archeologists. We then wanted to map their extension before the removal of covering sediments. Therefore, we attributed this reflection surface to the base of the concentration of bricks layer which, in fact, emerged later during the excavation.

Conclusions

In this paper a successful application of the HVSR geophysical method in archaeological surveying is presented and discussed.

Geological setting and urbanization conditions of the test area, where the archaeological ‘terramara’ site of *Pilastri* (northern Italy) is situated, do not allow a successful use of the geophysical methods most commonly employed in archaeological investigations, such as magnetometry, ERT and GPR. Because of these difficulties, we addressed the choice to the HVSR technique, which is largely used in seismic microzonation studies, but quite rarely used in archaeology. The aim of this research was to test the capability of the HVSR methodology for detecting paleo-surfaces, based on the hypothesis that these paleo-surfaces were compacted by trampling and thus generated an acoustic impedance contrast, possibly detectable as a resonance peak, at sufficiently high frequencies. However, ERT and GPR were performed as a supplement, providing poor archaeological related information (ERT) or limited results (GPR). The ERT section showed that the only recognizable structures are the limits of previous excavations of trenches ‘C’ and ‘D’ conducted two years earlier, while there are no other sub-horizontal discontinuities that can be interpreted as paleo-surfaces.

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The HVSR survey allowed to detect and map paleo-surfaces, whose presence and estimated depth were successively confirmed by direct excavations. Measurements were carried out on a 20 m spaced grid and locally tightened in correspondence of previous known and planned excavations. The method was tested also in array configuration, providing the same responses of the traditional single station configuration. This shall enable, in future surveys, a faster data acquisition phase, saving time and costs. To the best of our knowledge, this configuration is used for the first time in an archaeological context.

The success of this field application, as calibrated by direct excavation, shows that the proposed HVSR approach, as implemented in this paper [single/multi-station acquisition and two-dimensional (2D) visualization], is a valuable tool, capable of investigating interfaces of archaeological interest which spread over vast areas, and could be routinely used to find ancient shallow paleo-surfaces whenever other well-documented geophysical methods cannot be used and/or when a low-cost reconnaissance survey is requested.

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