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Atti del 34° Convegno Nazionale

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Tema 3: Geofisica applicata

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EAGE European Association of Geoscientists & Engineers – SEG – SEZIONE ITALIANA

15° Convegno Nazionale

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Indice

Moreover, according to our preliminary results the depth of the top of the marls could occasionally intersect engineering works across or below the Po riverbed.

The information we obtained, still under process and interpretation, were gathered in a half a day campaign, involving roughly eight people and two boats. Even at this stage of work, considering that the full implication of our findings is still to be exploited, these results seems of interest and another survey along other 5 km of the Po River, to the north of the one presented, is going to be planned.

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DIRECT INTERPRETATION OF SURFACE WAVES FOR 2-D AND 3-D SUBSURFACE IMAGING

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Introduction. The soil stiffness is routinely evaluated by direct investigation, using geotechnical tests such as CPT-CPTu, SPT. While this approach allows retrieving detailed and reliable information, the procedure is invasive and the result is punctual hence of limited spatial extension. Moreover, the costs of a survey quickly grow with the number of probes. A low cost, non-invasive, complementary strategy would be the use of methods based on surface waves (SW), such as SASW (Nazarian and Stokoe, 1984) or MASW (Park *et al.*, 1999; Socco and Strobbia, 2004). In the classic SASW and MASW, Rayleigh (and alternatively Love) SW are excited by an active source and recorded by a linear array of receivers deployed on the ground. The dispersive nature of the recorded surface waves is used to derive the vertical (1D) subsurface profile of the shear velocity V_S by an inversion procedure. In detail, the propagation of SW along the array allows for the construction of a dispersion pattern, which is retrieved by transforming the experimental seismograms from the time-space to a more suitable domain by using a specific numerical transform. For example, in the MASW framework, the frequency-wavenumber (f-k) and the frequency-Rayleigh (f-V_R) domains are frequently used and also occasionally the τ-p transform (McMechan and Yedlin, 1981). The obtained dispersion pattern is then an entire portion of a two parameters domain and in order to capture the dispersion pattern the spectral maxima are picked to yield the so-called dispersion curve. Since SW are multimodal, this approach is capable of separating multiple phase velocity values at the same frequency. In the SASW framework the dispersion pattern is retrieved by calculating the cross spectrum of experimental seismograms recorded at two, opportunely spaced, receivers. The dispersion pattern, in this case, is represented as a cloud of points in the frequency-velocity domain (f,V_R). Unfortunately, by this approach an unique value of the velocity is obtained for each frequency, so that when multiple modes contribute to the real propagation these are not identified as separated and misleadingly used as a whole "apparent" propagation mode during the inversion. Despite these differences however, the dispersion pattern is inverted to estimate shear wave velocity distribution.

Unfortunately, available inversion algorithms assume the subsurface model as a stack of homogeneous parallel layers, hence capturing only vertical variations of the subsurface elastic properties (e.g. Aki, 2002; Kausel and Roesset, 1981). Consequently, these algorithms are of limited use when lateral heterogeneities are known to exist. Indeed, there is a growing interest toward applications of the MASW technique for 2-D and 3-D subsurface imaging (Boiero and Socco, 2010; Vignoli *et al.*, 2011, 2015; Bignardi *et al.* 2012, 2014; Masoni, 2014; Socco *et al.* 2014, 2015). Such interest points out how the laterally heterogeneity identification is of primary interest in the near-surface investigations. Dealing with this issue, Bignardi *et al.* (2014) showed that in a MASW survey, the presence of a moderate lateral heterogeneity can be detected in the f-Offset domain while its effects are difficult to recognize when data are transformed in the f-V_R domain; i.e. in this domain the information of the "locality" is lost. This leads to the consideration that lateral heterogeneity could be retrieved by separately elaborating the signals recorded at pairs of receivers in a similar way as it is done in the SASW technique.

In what follows we shall use part of the SASW workflow to establish a strategy that can be used both as a feasible inversion strategy or alternatively for the direct interpretation of active-source datasets. Following the second course, we shall show that the Direct Interpretation of Phase Lags (DIPL) (Bignardi *et al.* 2015a, 2015b), which uses the frequency-dependent phase lags among pairs of seismic signals, is capable of retrieving a satisfactory 2-D and 3-D V_S subsurface image also in complex subsurface environments without the need of inversion. We shall discuss the workflow, the pros and cons of 2-D and 3-D applications. Finally, we shall present and discuss field examples.

Method. Let's consider a source S and two receivers, R_1 and R_2 placed along a line; a SASW-like data processing concerns calculating the phase of the cross spectrum between the signals recorded at the receiver pair. This information can be used to get the local dispersion pattern as a cloud of points (COP) in the f-V_R domain (see e.g. Fig. 1) through Eq. 1, [please refer to Nazarian's and Stokoe's (1984) paper for the details].

$$\phi(f) = \arg\left(F_2(f)F_1^*(f)\right), \quad (1)$$

and

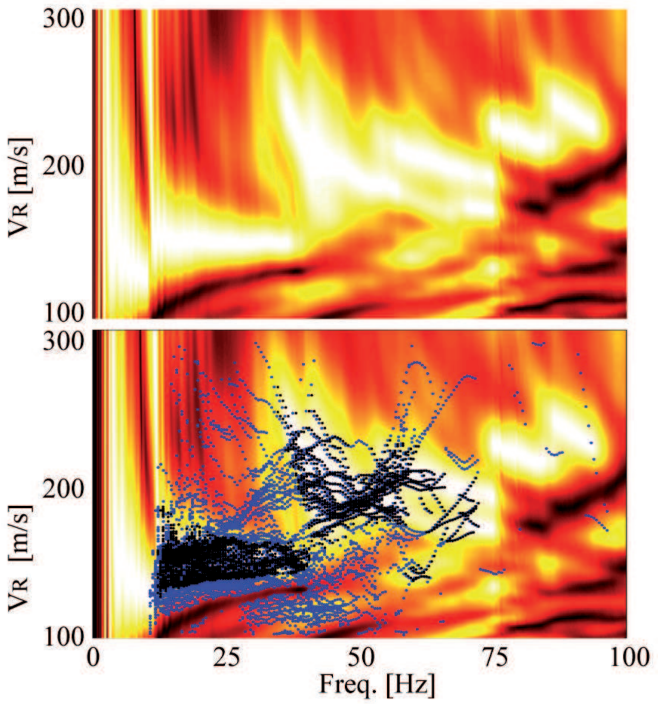

Fig. 1 – An example of the SASW-like cloud of points in the f-VR domain. In this example, the blue points are filtered out while the black points are those which comply with Eq. 2. For sake of comparison, the corresponding frequency-velocity transform is shown both clean (above) and with superimposed points (below) to show how the filtered COP adapts to the propagating modes.

$$V_R(f) = \frac{2\pi d}{\phi(f)} f$$

where f is the frequency, $\phi(f)$ is the phase lag at the frequency f and d is the distance between the two receivers.

This cloud of points, which is just a suitable transformation of the original data, still retains the locality information and to this level, the information regarding different modes of propagation, although mixed. These frequency-dependent phase lags would be suitable to build an objective function to be used during inversion, for example, in a Full Waveform Inversion style (Virieux and Operto, 2009; Masoni *et al.*, 2014; Groos *et al.*, 2014), assuming a suitable forward model is available. In classical SASW, however, this information is usually inverted using a parallel-layered based forward model. In order to avoid introducing such approximation, we proceed without inversion. We rather express the COP in the wavelength-velocity domain (λ-V_R) which is then associated to the subsurface between the pair.

2-D approach. In the two dimensional approach, source and receivers are all placed along the same line. The advantage of this approach is basically that starting from the same data we can compute the frequency-velocity spectrum and use its amplitude to filter out the points in the COP corresponding to harmonics that do not carry a meaningful amount of energy (say less than 5%). To do so, we require

$$E\,(f,V_R)_p > 0.05 E_{max}(f), \quad (2)$$

where $E\,(f,V_R)_p$ is the energy carried by the harmonic wave represented by point p, having frequency f and traveling at speed V_R, and $E_{max}(f)$ is the maximum energy transferred by any harmonic wave at the same frequency. An example of the points calculated for a whole linear array of 24, 4.5 Hz proper frequency geophones is shown in Fig. 1. The blue points are the points that are discarded once equation 2 is taken into account, while the valid points are drawn in black. The valid points agree quite well with the frequency-velocity transform obtained for the same data and shown in the background.

The remaining points are then expressed in the wavelength-velocity domain (λ-V_R). The COP obtained from all receiver pairs, for all the source points and for all the shots (when multiple shots are performed), can now be assembled into one pseudo-section by means of a suitable weighted average algorithm. We refer to this result as a “pseudo-section” because the maximum depth to which each (λ,V_R) point brings its contribution is associated to a suitable fraction β of the wavelength, in consideration of the fact that the investigation depth of a (Rayleigh) surface wave is linked to its wavelength. Here we assumed β = 1. For the assembly process we consider the 2-D subsoil as discretized into squared blocks where the value of the velocity for each block is calculated by a weighted average procedure. Averaging has recently proved very useful for immediate (or rough) Vs estimation and allows retrieving very satisfactory results even without inversion (Socco and Comina, 2015). Indeed, we built our weighting strategy based on some phenomenological observations, but better strategies may exist.

$$V_S(x,z) = 1.1 * \sum_{ij} \sum_{k}^{n_p} b_{ij}\left(z, l_{k,ij}\right) V_{R\,k,ij}, \qquad (3)$$

where

$$b_{ij}\left(z, l_{p,ij}\right) = \left(\frac{|z|}{l_{p,ij}}\right)^2 \quad \text{if } |z| \le l_{k,ij}, \qquad (4a)$$

$$b_{ij}\left(z, l_{k,ij}\right) = 0 \qquad \text{otherwise;} \qquad (4b)$$

ij represent the receiver pair, $p_{k,ij} = (\lambda_{k,ij}, V_{S_{k,ij}})$ is the corresponding COP, k is an index running on the accepted points in the cloud and $1 = \beta\lambda$ is a suitable fraction of the wave-length λ. The 1.1 factor is thought to empirically translate V_R into V_S.

It is well known that SASW does not allow resolving all the different propagation modes but only one whole apparent mode is retrieved. Note that the weighting average naturally takes into account the presence of multiple modes because multiple values of velocity associated to the same frequency affect different portions of the pseudo-section once expressed in the wavelength-velocity domain. An example of 2-D pseudo–section is shown in Fig. 2a. To judge

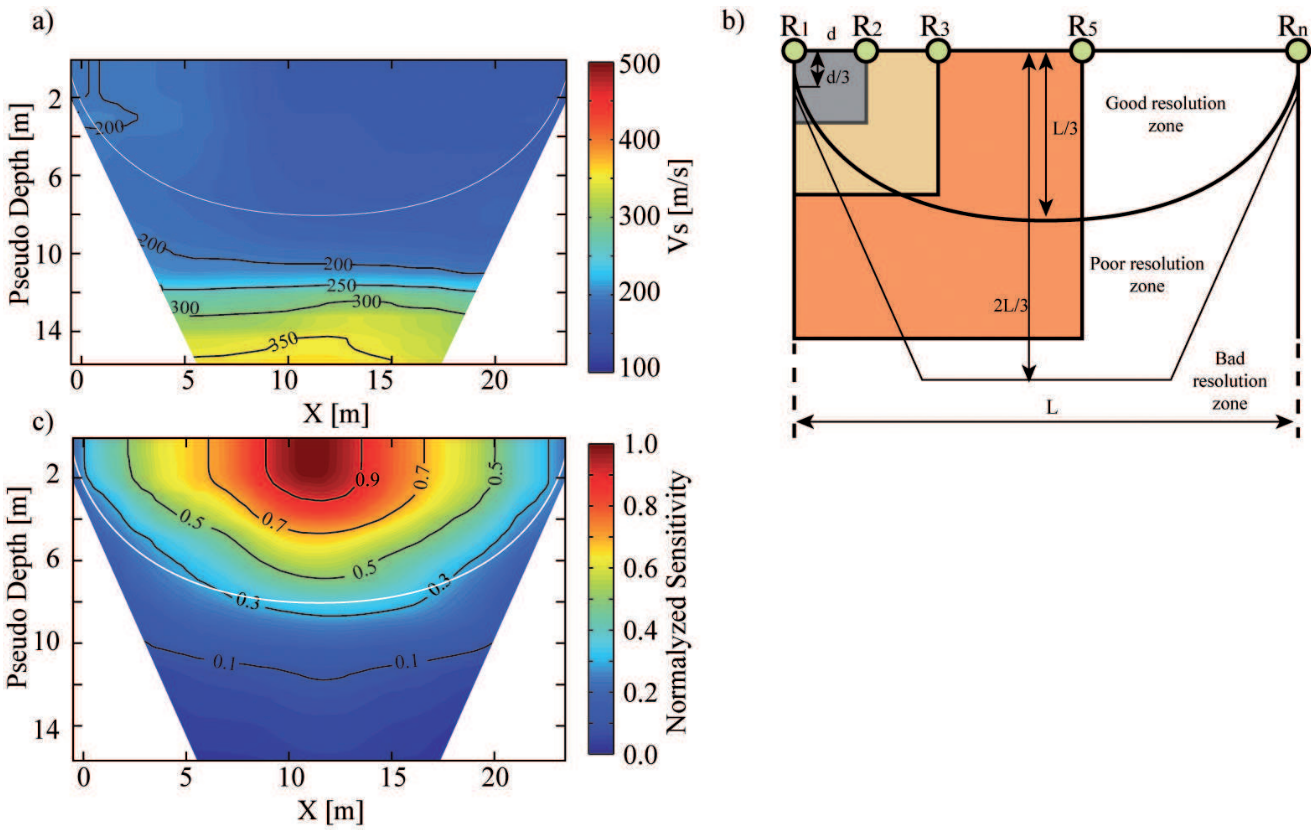

Fig. 2 – a) Obtained 2-D Vs pseudo-section for a MASW-like survey. b) Example of the influence of different receiver pairs on the interpreted profile(a) and sensitivity of the proposed method with depth. The maximum depth showing a reliable resolution is roughly $\lambda_{max}/3$, where d <λ< L, d is the inter-geophonic distance and L is the length of the array. Velocities in the poor resolution zone are evaluated using only distant receivers so that deeper velocity values are correct but horizontally stretched. c) Computed normalized sensitivity corresponding to the Vs profile in (a).The white curve in a and b, highlights the portion with “good resolution” (i.e. in this case, the shallower 6 m, with a number of contributions roughly higher than 30%, in this case).

the reliability of such result we can investigate how the final pseudo-section depends on the imputed data. Of course, since this is not an inversion, a traditional definition of "sensitivity" is neither possible nor applicable. To achieve the result in this context, we define "sensitivity to the data" the normalized number of contributions per block. Since the velocity value in each squared block is obtained by averaging multiple contributions, the most the contributions, the most reliable will be the result. The sensitivity corresponding to the pseudo-section of Fig. 2a is shown in Fig. 2c, while Fig. 2b shows a schematic example on how different receiving pairs contribute to the final Vs interpretation and to its sensitivity pattern. The depth, to which lateral heterogeneity is correctly retrieved, is roughly L/3, where L is the array length. Beyond this depth, a result can still be retrieved but, since only distant receivers are involved, the interpreted velocity values are spread horizontally and their exact location under the array is lost.

3-D approach. A relevant number of factors come into play when a three dimensional (3-D) subsurface is considered, for instance, near-foundation soils in urban areas. The presence of localized V_S variations such as the foundation itself, heterogeneities due to excavations and successive replenishments, sewers, fuel tanks, surface velocity inversions due to artificial pavements, or even tree roots, makes up a severe and challenging 3-D subsurface. Furthermore, since the space available at the surface may be insufficient, receivers must be placed keeping into account both the accessibility of the specific site and the need to record a dataset with sufficient wavenumber coverage.

In practice, to tackle the 3-D Vs subsoil reconstruction challenge a method for the elaboration of surface waves recordings unbound from both a rigid field geometry and from the 1D assumption would be highly desirable.

To extend the approach to the three dimensional world, since SW spreading from a point source is cylindrical, we can still use the procedure reported in Eqs. 1-4 under the assumption that the angle α between R_1 and R_2 is small enough. This enables to link the portion of the cylindrical shell defined by R_1 and R_2 and the angle $\alpha = R1SR2$ (i.e. a portion of the target volume) to the COP obtained for the receiver pair under investigation. Note that the strategy to obtain the COP and its extension to 3-D may represent a very promising strategy for the 3-D inversion of the data.

The assembly process is still performed using the COP's relative to all the receiver pairs, all the sources and multiple shots but the 3-D subsurface is now discretized in cubic blocks where the value of the velocity is calculated according to Eqs. 3, 4a and 4b.

The result is a 3-D pseudo-volume of V_S where the velocity values are most properly retrieved to a depth roughly equal to L/3, where L is the maximum distance between the two farthest receivers. In the 3-D case with arbitrarily located sources and receivers, it is of course not possible to filter the COP using a frequency-velocity transform, as is allowed by several (usually 24, at least) regularly spaced traces, and this can potentially enable for artifacts introduction. The only constraint we can impose is based on the energy produced by each single shot

$$E(f, V_R)_p > 0.05\, E_{max}(r_1, r_2), \quad (5)$$

where, for each pair, is the energy transferred by the most energetic harmonic. For this reason, the 3-D sensitivity with respect to the data is the main tool not only to judge the reliability of the result at any location (*x,y,z*) but also to have an indication about the spectral accuracy in terms of wavenumber coverage. Finally, Fig. 3 shows a three dimensional survey where the signals recorded at 24 vertical, 4.5 Hz proper frequency geophones and produced by 21 different sources where used to characterize the subsurface under the foundations of a residential building, with particular emphasis to one of its corners, where a settlement occurred. The obtained Vs (Fig. 3a) also presents anomalies due to the sewer system and as expected, a lowering of the shear velocity under the investigated corner where the walls presented some cracks, probably connected to the degradation of the supportive function of the foundation soil.

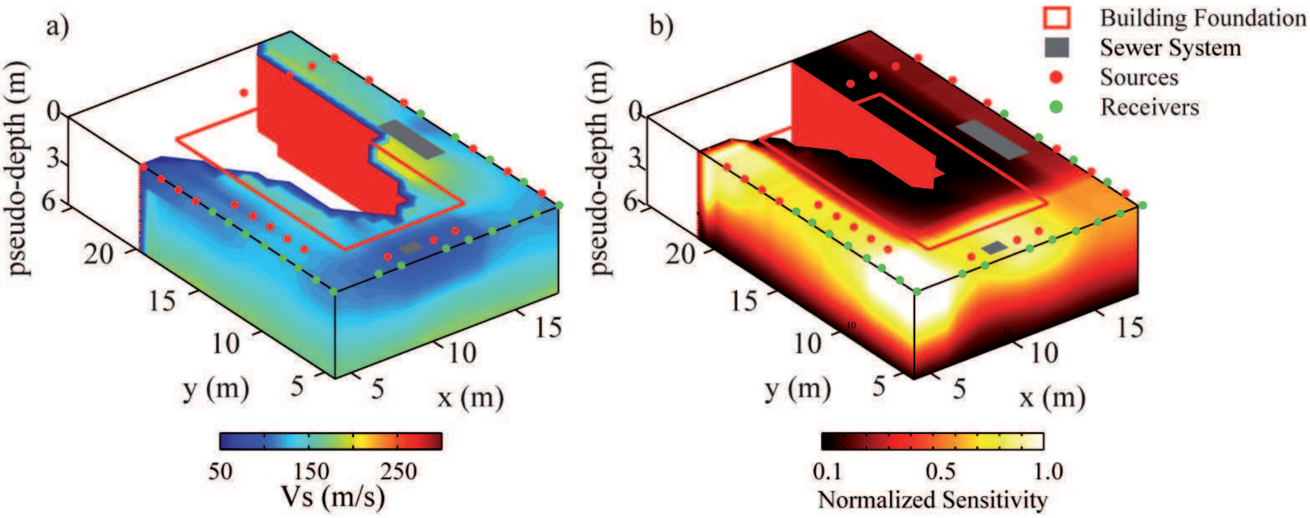

Fig. 3 – Results of the Phase Lag Direct interpretation for a 3-D, near foundation subsurface. The footprint of the building is highlighted in red. a) Vs distribution beneath a building retrieved using a 2-D array of 24 receivers (showed as green dots) and 21 sources (showed as red dots). The picture highlights two anomalies due to the sewer system (gray squares) and a low velocity zone around the corner (x=7,y=7), that was the target of the investigation. b) Corresponding sensitivity pattern. Only the zones with a sufficient spectral resolution, in terms of wavenumber coverage, are shown. The high values around the target corner mean that the result in this portion of the subsurface is reliable while reliability lowers toward the back of the house and at depths higher than three meters.

Conclusions. A strategy for the use of the phase lags between pair of signals recorded by either an array or by an arbitrary 2-D distribution of receivers and produced by multiple sources was presented. This strategy could in principle be used to build, in future, an inversion process. However, in this work we rather presented a Direct Interpretation of the Phase Lags (DIPL) to tackle both the 2-D and 3-D investigation of the subsurface. We showed that the use of equations 1-4, coupled with the comparison to the frequency-velocity transform allows retaining the local property of the data and at the same time takes into account both the fundamental and higher modes of the surface wave's propagation, thus enabling the construction of reliable 2-D Vs pseudo-sections capable of detecting and evaluating lateral heterogeneities below a MASW-like profile. Further, we extended this approach to three dimensions and we discussed the capabilities and limitations of both 2-D and 3-D approaches.

Finally, examples of application to field data were given; where the 2-D case concerns data collected over a regular (i.e. practically 1-D) subsurface while the 3-D data were collected to characterize a very shallow portion of the subsurface under the foundation of a residential building. In both cases we found the results in agreement with both cross-hole and CPT investigations purposely carried-out at the same sites, and whose results cannot be shown here because of the limits imposed on the number figures.

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INTEGRATED GEOPHYSICAL PROSPECTING IN THE ARCHAEOLOGICAL SITE OF BADIA

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Abstract. One of the aims of modern archaeology is the identification of relationships between human communities and their habitat over time. Understanding those links can spread light over the historical development of landscape and the relation between people and environment. In this work, we focus our attention on a settlement in the Apulia region (southern Italy), where remains dating back to Late Antiquity and Early Medieval age have been investigated. The study area, nowadays known as *Contrada Badia*, is located close to the modern town of Cutrofiano (Lecce). The site has been the object of many archaeological investigations concerning the Classical Roman period evidences. On the other hand few investigations focused on the Late Antique and Early Medieval age. However, recent archaeological excavations revealed important features testifying to the dynamic transformations which occurred in these periods. The above described situation represent an ideal context to develop a framework in which integrated archaeological, geophysical and archaeometric investigations could be of great help in the understanding of historical dynamics. In particular an archaeological survey has been performed at *Contrada Badia* over an area of about 50 hectares: this led to the identification of two particularly relevant sites. The first one can be identified as a rural settlement dating back to the Imperial and Late Antique period, whereas the second site is likely referable to a medieval abbey.