# Near Foundation Soil Stiffening Evaluation after Resins Injection by a Novel 3D Interpretation of Surface Waves Data

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# Near Foundation Soil Stiffening Evaluation after Resins Injection by a Novel 3D Interpretation of Surface Waves Data

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## SUMMARY

The characterization of soil settlements below foundations of buildings using surface waves methods represent an extreme challenging problem because of the presence of localized shear waves variation and shallow heterogeneity. To tackle the near-foundation shear waves distribution reconstruction challenge a method for the elaboration of surface waves recordings unbound from both rigid field geometry and from the classic layered subsurface assumption would be highly desirable. We introduce a novel elaboration strategy of surface waves data, based on the Direct Interpretation of Phase Lags (DIPL-3D)among pairs of seismic signals which aims to retrieve the three dimensional shear waves velocity subsurface distribution without using inversion. As an example application, the method is used for the evaluation of near foundation soil stiffening after an expanding resins injection intervention

**Introduction**

The soil stiffness is routinely evaluated by direct investigation, using geotechnical tests such as CPT-CPTu. While the direct approach gives detailed and reliable information, it is invasive and only valid point wise; moreover the costs of a survey quickly grow with the number of probes. A low cost, complimentary strategy would be the use surface waves methods (SWM), such as SASW, (Nazarian and Stokoe, 1984) or MASW (Park et al., 1999, Socco and Strobbia, 2004), which use the dispersive nature of Surface Waves (SW) excited by an active source and recorded by a linear array of receivers deployed on the ground to retrieve the vertical (1D) subsurface profile of shear velocity $V_S$. In these methodologies, the propagation of SW along the array allows for the construction of a dispersion pattern, which is retrieved by transforming the acquired seismograms from the time-space to a more suitable domain, typically, the frequency-Rayleigh wave velocity (f-$V_R$) domain. In detail, the dispersion is represented by a set of points (f,$V_R$) in SASW, while in MASW the data are transformed either using the f-k or the τ-p transforms (McMechan and Yedlin, 1981) and finally expressed as an f-$V_R$ power spectrum where the spectral maxima are picked to yield the so-called dispersion curve. In both cases, the dispersion pattern is inverted to estimate the 1D distribution of $V_S$. This allows estimating the soil stiffness via the shear modulus μ as it is directly related to $V_S$ through $\mu = \rho V_s^2$ (ρ is density).

Unfortunately, available inversion algorithms assume the subsurface model as a stack of homogeneous parallel layers, hence capturing only the 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 2D and 3D subsurface imaging (Boiero and Socco, 2010; Vignoli et al., 2011; Bignardi et al. 2012; Masoni, 2014; Socco et al. 2014 ).

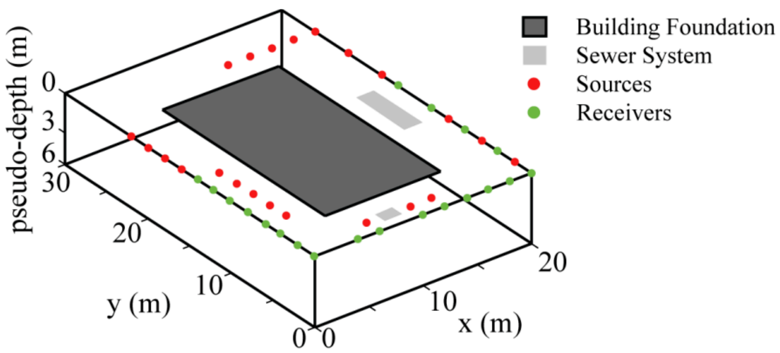


*__Figure 1__ 3D scheme of the surface sources and receivers distribution. The foundation footing is highlighted in dark gray, while locations of some parts of the sewer system are highlighted in light gray. The source receiver's distribution was optimized to investigate the corner of the building closest to the axis origin while the entire perimeter was injected.*

A relevant issue is the characterization of soil settlements below foundations of buildings, where the presence of localized $V_S$ variations such as the foundation itself, heterogeneity due excavations and successive replenishment, sewer tanks and surface velocity inversions due to artificial pavements make a severe and challenging 3D subsurface. To tackle the near-foundation Vs soil reconstruction challenge a method for the elaboration of surface waves recordings unbound from both rigid field geometry and from the 1D assumption would be highly desirable.

In the following, we shall introduce a novel elaboration strategy for seismograms generated by a set of arbitrarily located sources and recorded by a set of arbitrarily deployed receivers (fig. 1), based on the Direct Interpretation of Phase Lags among pairs of seismic signals which aims to retrieve the 3D $V_S$ subsurface distribution (DIPL-3D). Further, as an application, we shall retrieve the 3D $V_S$ distributions before and after a resins injection performed under the building perimeter to improve the supporting capacity of foundation soil, to evaluate the soil stiffening in terms of $V_S$ increase.

The expanding resins injection is to date routinely used for recovering the foundation stability and prevent further damages to cracked walls (Occhi et al., 2008). The Injection requires an adequate monitoring system capable of scientifically evaluate the outcome of the intervention. The Electric resistivity tomography proved to be successful to locate the degraded volumes in a pre-treatment survey and to evaluate the effects of resins to re-homogenize the treated volumes along and after the injection (Santarato et al., 2011). The stiffness improvement is then evaluated trough CPT/CPTu. In this context, SWM potentially represent a fast and low cost alternative to the direct sampling, however, the resin injection introduces a localized heterogeneity that would not be correctly highlighted by the afore-mentioned 1D methods. Furthermore, the very shallow nature of the problem at hand and the often limited space available at the site for deploying the receivers constitute additional issues which make those techniques unpractical.

Concerning lateral heterogeneity, 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 effect are difficult to recognize when data are transformed in the f-$V_R$ domain. This leads to the consideration that lateral heterogeneity could be retrieved by separately elaborating the signals recorded at pairs of receivers. Let's consider a source $S$ and two receivers, $R_1$ and $R_2$ in line; a SASW-like data processing (i.e. calculating the phase of the cross spectrum between the signals recorded at the receiver pair) 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. 2)

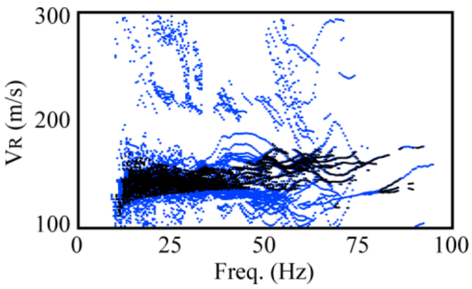


***Figure 2*** *An example of the SASW-like cloud of points in the f-$V_R$ domain. In this example, the blue points are filtered out while the black points are those which comply with eq. 2.*

In SASW, this information is inverted using a parallel-layered based forward model; however, in order to avoid introducing this approximation, we do not proceed to the inversion. We rather express the COP in the wavelength-velocity domain (λ-$V_R$) which is then associated to the subsurface between the pair. Further, since SW spreading in three-dimensions is cylindrical, we can still use this procedure when the angle α between $R_1$ and $R_2$ is small to retrieve a pseudo-volume of $V_R$ in the portion of the cylindrical shell defined by $R_1$ and $R_2$ and the angle $\alpha = \widehat{R1\,S\,R2}$. We refer to this result as a "pseudo-volume" because the depth 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 $\alpha < 15^{o}$, and $l = \beta\lambda$, with $\beta = 1$. We then consider the subsoil as discretized and we perform a direct assembly of the COP using the weighted average

$$V_S(x,z) = 1.1 * \sum_{ij} \sum_{k}^{n_p} b_{ij}\left(z, l_{k,ij}\right) V_{R_{k,ij}}, \qquad (1)$$

where

$$b_{ij}\left(z, l_{p,ij}\right) = \left(\frac{|z|}{l_{p,ij}}\right)^2 \ \text{if} \ |z| \le l_{k,ij},$$
$$b_{ij}\left(z, l_{k,ij}\right) = 0 \qquad \text{otherwise;}$$

$ij$ represent the receiver pair, $p_{k,ij} = \left(f_{k,ij}, V_{S_{k,ij}}\right)$ is the corresponding COP, $k$ is an index running on the points in the cloud and $l$ is a suitable fraction of 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. To solve this drawback only those points associated to waves carrying a meaningful amount of energy are considered in eq. 1. 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.

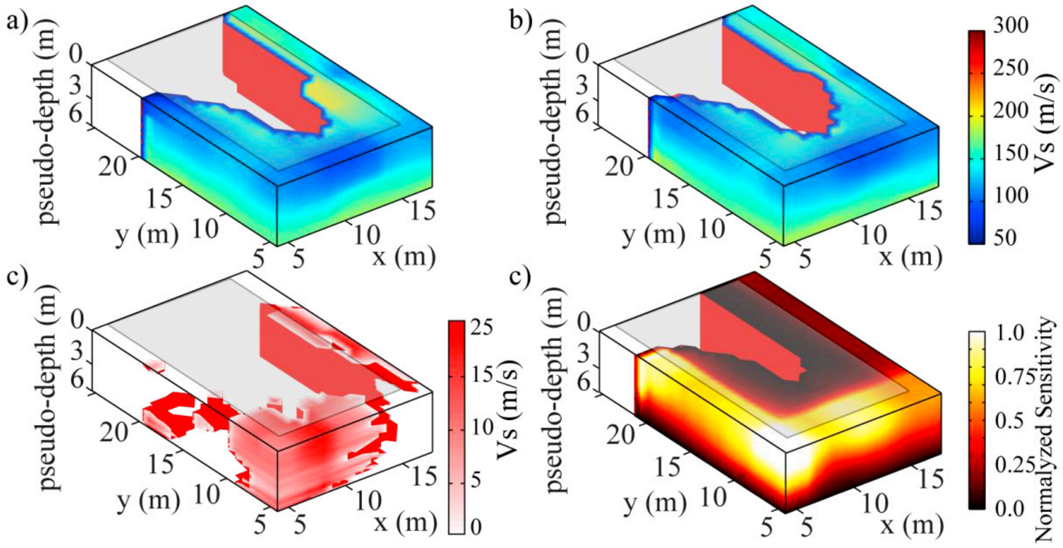


***Figure 3*** *Apparent $V_S$ (a) before and (b) after the resin injection. c) Stiffening effect in term of percent increase of $V_S$. d) Normalized sensitivity accounting for the reliability of the results. Portions of the model for which to retrieve any result was not possible with the present sources-receivers configuration are not colored. The footprint of the building is highlighted with the gray rectangle.*

By doing so, the data are still being transformed in the f-$V_R$ domain but for each receiver pair the obtained velocity is assigned to the subsoil volume between the analyzed pair so that the local character of the information is preserved and higher modes naturally included. The result is a 3D pseudo-volume of $V_S$ which of course is just a velocity interpretation, meant to be used as an initial guess for a subsequent full waveform inversion (not discussed here). Nonetheless, a major advantage of this approach is that it results in a fast and efficient tool to detect 3D heterogeneities. The (apparent) depth, to which $V_S$ is most properly retrieved is roughly L/3, where L is the distance between the two farthest receivers. Beyond this depth, a result can still be retrieved but, since only distant receivers are involved, the interpreted velocity values are horizontally spread. In order to judge the reliability of the result, consider that at any location (*x,y,z*), the more contributions are averaged in eq. 1 to obtain $V_S$ (*x,y,z*) the more the result will be reliable. The normalized sensitivity of the result with respect to the data is shown in fig. 3d. Finally, figures 3a and 3b represent the obtained $V_S$ before and after the stiffening intervention and percent variation of about 5 to 25% which we believe to be due to the resins compacting action is shown in figure 3c.

**Conclusions**

A strategy for the 3-D interpretation of surface waves based on the Direct Interpretation of Phase Lags (DIPL-3D) was presented. DIPL aims to infer a 3D $V_S$ pseudo-volume (whose depth is somewhat proportional to the true depth) from the direct interpretation of the SW dispersion pattern without the need for inversion, however, it is capable of naturally taking into account the influence of higher modes. Even originally meant to produce a suitable starting model for a later FWI, the approach proved to be very efficient for the fast 3D non-invasive evaluation of subsurface soil stiffening due to a resin injection intervention. A 3D volume with a $V_S$ increase between 5 to 25% which we believe to be representative of the stiffening effect of resins was highlighted. This increment was found in agreement with a cross-hole and CPT investigations purposely carried-out for stiffness control.

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