Passive seismic methods for site characterization

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ABSTRACT

Site characterization methods to extract the shear-wave velocity (*Vs*) structure over the first few tens to few hundred of meters or the soil's resonance frequency using seismic noise recordings have become widespread over the last 40 years. Being cost-effective and easy to implement, especially in urban environment, passive seismic methods have been shown reliable to retrieve the soil resonance frequency and the *Vs* profile of near-surface geological layers. International efforts over the last 20 years have outlined the capabilities and limitations of passive seismic methods and lead to a series of good-of-practice, state-of-the-art and recommendations on data acquisition and processing. Recent methodological developments using three-component single-station and three-component array methods are promising approaches to better constrain *Vs* profiles. Also, the very high spatial and temporal resolution offered by the Distributed Acoustic Sensing (DAS) makes this emerging technology one with very high potential for near-surface site characterization, especially in urban environment.

Keywords: passive seismic methods, site characterization, H/V and array methods, Distributed Acoustic Sensing

1. Introduction

Site characterization methods to extract the shear-wave velocity (*Vs*) structure over the first few tens of meters to a few hundred meters or the soil resonance frequency using seismic noise recordings (also named passive seismic methods or non-invasive methods) have become widespread over the last 40 years. The main reason for this success is their ease of implementation, particularly in urban environments, and their lower cost compared with conventional methods based on borehole seismic. After a brief history of the development of passive seismic methods, this paper summarizes the main outcomes from international efforts to evaluate the performance and limitation of passive seismic methods. Then, the recent methodological developments using single-station methods or array methods are presented, as well as the huge potential of Distributed Acoustic Sensing (DAS) for site characterization.

2. Short historical review

Since the first publication on seismic ambient noise at the end of the 19th century (Bertelli 1872), the first half of the 20th century was marked by numerous studies on the origin (atmospheric depressions, storms, wind, offshore waves, ...) and the nature (Rayleigh waves, Love waves, stationary waves) of low-frequency seismic noise (periods between 3 and 10 s), see (Bonnefoy-Claudet et al, 2006) for a review.

The Cold War context and the need to reach an agreement on the technical feasibility of monitoring nuclear tests led to the development of dense seismological networks and, hence, to the development of array processing methods primarily developed for detecting and locating events, e.g. (Capon, 1969), (Lacoss et al., 1969), see (Rost and Thomas 2002) for a summary.

Followed a time when 'classical' seismology was turning away from seismic noise. Meanwhile (Aki 1957) became interested in the spatial correlation properties of noise in order to extract the dispersive properties of surface waves and developed the SPAC (Spatial Auto Correlation) method, which has been the source of many subsequent variants : ESAC (Ling and Okada 1993), (Ohori et al. 2002), MMSPAC (Asten 2006), MSPAC (Bettig et al. 2001), 2s-SPAC (Morikawa et al. 2004) and applications aimed at recovering the *Vs* profile of superficial geological formations (from a few meters to a few hundred meters). In addition to the SPAC method, array methods directly measuring the phase differences between the seismic noise recorded simultaneously at array stations were also used, in their conventionnal (Frequency-Wavenumber, FK) (Lacoss et al. 1969) and high-resolution (High-Resolution Frequency-Wavenumber, HRFK) (Capon, 1969; Asten and Henstridge, 1984) formulations, to extract dispersion characteristics of surface waves propagating in shallow geological layers. As mentioned by (Bonnefoy-Claudet et al. 2006), the noise array methods have been very popular in engineering seismology, mainly for applications in urban environments, e.g. some applications in various places worldwide among many others : (Sato et al 2001), (Kudo et al. 2002), (Di Giulio et al. 2006), (Stephenson et al. 2009), (Zor et al. 2010), (Salloum et al. 2014), (Molnar et al. 2015), (Farrugia et al. 2017), (Teague et al. 2018), (Cushing et al., 2020).

However, the uptake of noise array methods was not as spectacular as that of the single-station H/V method popularized by Nakamura (1989), which consists of computing the ratio between the horizontal and vertical spectral components of the seismic noise in order to extract the soil's fundamental resonance frequency. Due to its ease of use and low cost, the H/V method was widely used to (i) image and/or estimate the depth of seismic bedrock, e.g. (Ibs-von Seht et al. 1999), (Hinzen et al. 2004); (ii) estimate and/or map the frequencies likely to be amplified during earthquakes, e.g. (Lermo and Chavez-Garcia 1993) (Field and Jabob 1995) (Haghshenas et al. 2008) (Picozzi et al. 2009a); (iii) study the relationship between observed damages and soil's resonance frequencies, e.g. (Leyton et al. 2013). Recent reviews on the use of the H/V method are provided in (Molnar et al. 2018), (Molnar et al. 2022).

Since 2004, there has been a phenomenal revival of interest in seismic noise in 'classical' seismology. (Shapiro and Campillo 2004) have indeed shown that correlation of the seismic noise recorded at two stations makes it possible to extract the Green's function of the medium between these two stations (hereafter named the seismic noise interferometry method). Taking advantage of the instrumental developments of the last twenty years (lower instrumental cost that led to deployment of dense arrays) and the development of computing resources, the seismic noise interferometry has been widely used for seismic tomography at global and crustal scales. However, this method has been less often used at near-surface scale (i.e. first tens of meters), e.g. (Gouédard et al. 2008), (Picozzi et al. 2009b), (Pilz et al. 2012), (Hannemann et al. 2014), (Inzunza et al. 2019), (Anthymidis et al. 2022).

3. Performance of passive seismic methods for site characterization

A number of international benchmarks/blind tests have been carried out over the last twenty years to evaluate the performance of passive and active surface waves methods for recovering the *Vs* structure (Table 1). These different benchmarks have highlighted:

a) The measurement of phase velocities is extremely robust, whatever the processing method used. When provided, the uncertainty in the phase velocity estimate varies from 5 to 20%

b) Participants are often too optimistic about the ability of methods to extract phase velocities at low frequencies, and thus about the maximum depth reached

c) In the first few tens of meters, the variability of the inverted *Vs* profiles is very similar to the variability obtained by invasive methods (cross-holes, down-holes, PS-logging), the variability being greater in the top 5 to 10 meters for both methods.

d) Estimating the depth and velocity of seismic bedrock or known interfaces, as well as the uncertainty in the inverted *Vs* profiles is still a challenge

e) Passive and active surface waves methods are not able to retrieve the fine *Vs* layering

f) Time-averaged V_S estimates (V_{S10}, V_{S30}, and V_{S100}) are reliable

These benchmarks stimulated the recent writing of good-of-practice/state-of-the art papers, e.g. (Foti et al. 2018), (Hayashi et al. 2022), (Gosselin et al. 2022).

The performance of passive seismic methods to retrieve *Vs* profile and soil fundamental resonance frequency together with their cost effectiveness and easiness to implement in urban environment compared to invasive methods (Cultrera et al. 2021) made these methods the most used today for extensive site characterization at seismological permanent sites, e.g. (Michel et al. 2014), (Felicetta et al. 2017), (Hollender et al. 2018). Recommendations on required minimum information on data acquisition and processing together with quality metrics have been recently proposed to reach an homogeneous set of high-level metadata for site characterization at seismological sites (Cultrera et al. 2021), (Di Giulio et al. 2021).

Table 1. List of benchmarks comparing non-invasive methods (active of passive surface waves methods) and invasive ones (drilling methods).

Benchmark	Number of sites	Reference Vs profile	Methods
(Asten and Boore 2005) (Boore and Asten 2008)	2	yes	Passive and active methods
(Cornou et al. 2006)	6 (including 4 virtual sites)	yes	Passive methods
(Cox et al. 2014)	1	no	Passive and active methods
(Garofalo et al. 2016a) (Garofalo et al. 2016b)	3	yes	Passive and active methods
(Asten et al. 2022)	4	yes	Passive methods
(Chimoto et al. 2023)	1	yes	Passive and active methods

4. Recent development and emerging technologies

4.1. Single-station and array methods

4.1.1. Inversion of H/V curve and Rayleigh wave ellipticity

Inversion of H/V curve to recover the shear-wave velocity structure has been a hot topic in the scientific community during the last three decades. H/V inversion requires forward modelling of the H/V curve in the inversion algorithm.

In 1D tabular media and elastic materials, the H/V can be modelled from the ratio of the power spectral densities of the Rayleigh and Love modes excited by a random and isotropic distribution of surface point sources placed around the receiver, among others (Tokimatsu et al. 1992), (Arai and Tokimatsu 2004), (Parolai et al. 2005), García-Jerez et al. 2007). (Lunedei and Albarello 2010) and (Lunedei and Albarello 2015) extended the approach to account for all wave types (body and surface waves) and the attenuation of the medium.

Based on diffuse field theory, (Sánchez-Sesma et al. 2011) formulated the relationship between the H/V and the imaginary parts of the Green's functions of the horizontal and vertical components. This formulation allows the contributions of all wave types and the attenuation of the medium to be accounted for. As outlined in (Molnar et al. 2022), this approach has led to recent numerous developments and applications, e.g. (Lontsi et al. 2015), (Piña-Flores et al. 2016), (Lontsi et al. 2019), (Sánchez-Sesma et al. 2017), (Tchawe et al. 2020), (Ito et al. 2021), (Carrasco et al. 2023), (Farazi et al. 2023), (Lontsi et al 2023).

Rather than inverting the H/V curve, an alternative is to invert the ellipticity of the Rayleigh waves. As shown by (Boore and Toksöz 1969), (Fäh et al. 2001), (Malischewsky and Scherbaum 2004), the ellipticity of Rayleigh waves, and particularly its right flank, carries information on the *Vs* structure. Assuming the proportion between Rayleigh and Love waves in the seismic noise wavefield, e.g. (Castellario and Mulargia 2009), or extracting Rayleigh waves from the noise wavefield, e.g. (Hobiger et al. 2009), (Poggi et al. 2012), inversion of Rayleigh wave ellipticity has been performed by, among others, (Yamanaka et al. 1994), (Konno and Ohmachi 1998), (Fäh et al. 2001), (Fäh et al. 2003), (Scherbaum et al. 2003), (Castellaro and Mulargia 2009), (Poggi et al. 2012), (Hobiger et al. 2013).

The inversion of the H/V curve and/or ellipticity of Rayleigh waves are promising methods for recovering the *Vs* structure, provided however that prior information on the subsurface structure is available or that H/V or ellipticity are jointly inverted with dispersion estimates of surface waves, e.g. (Piccozi et al. 2009) (Hobiger et al. 2013), (Poggi et al. 2012), (Lontsi et al. 2015), (Farazi et al. 2023).

4.1.2. Three-component array analysis

Most of the noise array analysis are performed on the vertical component of recorded seismic noise wavefield with the aim to extract dispersion curves of Rayleigh waves. Several methods based on three-component array analysis were however proposed in the recent years to extract both Love and Rayleigh waves dispersion characteristics in terms of dispersion curves and, for some approaches, Rayleigh wave signed ellipticity curves (Köhler et al., 2007), (Fäh et al. 2008), (Poggi and Fäh 2010), (Hobiger et al. 2012), (Maranò et al. 2012), (Riahi et al. 2013), (Maranò et al. 2017), (Wathelet et al. 2018), (Wathelet et al. 2024). Capturing the complexity of the noise wavefield, the 3C array methods help identifying Rayleigh and Love modes of propagation. The various modes of surface waves in terms of dispersion curves and ellipticity curves of Rayleigh waves are then often jointly inverted to better constrain the *Vs* profile, e.g. (Michel et al. 2014), (Hollender et al. 2018), (Fotouhimehr et al. 2021), (Hobiger et al. 2021), (Vantassel et al. 2024).

4.2. Fiber-optic Distributed Acousting Sensing

Fiber optic based data such as DAS (distributed acoustic sensing) have today become potentially very interesting for various applications in earthquake seismology, engineering seismology, structural health monitoring and ground structure imaging, e.g. (Barrias et al. 2016), (Lindsay et al. 2017), (Martin et al. 2018), (Spica et al. 2020), (Abbas et al. 2024). Indeed, compared to conventional seismic sensors, DAS offers a much higher spatial and temporal resolution which makes this emerging technology very appealing, especially when using existing telecommunication infrastructure (also termed dark fibers) in urban environment.

In terms of site characterization, comparison between Rayleigh wave dispersion curves derived from DAS and controlled active source experiments (vibroseis, ground impact) using the Multichannel Analysis of Surface Waves (MASW) (Park et al. 1999) outlines the ability of DAS to retrieve correctly the dispersion curves down to wavelength of one acquisition gauge length, e.g. (Song et al. 2019), (Rossi et al. 2022) (Vantassel et al. 2022). Rayleigh surface waves propagating along DAS lines can also be reconstructed using seismic interferometry on seismic noise generated by anthopogenic sources (urban traffic, trains, etc) to get virtual source gathers, from which dispersion curves might be then retrieved using MASW or phase shift methods, e.g. (Ajo-Franklin et al. 2019), (Song et al. 2021), (Shao et al. 2022). Reconstruction of seismic surface waves along DAS lines using seismic ambient noise, -while disregarding spurious events related to persistent anthropogenic noise sources that may violate the assumption of uniform distribution of sources in the noise interferometry method-, has been recently proposed (Cheng et al. 2023). A few studies focus on using 2D horizontal DAS array in order to study the effects of Love and Rayleigh waves superimposition on the reconstructed seismic surface wavefield (Luo et al. 2020) (Zhao et al. 2023).

As regards soil fundamental resonance frequency, (Spica et al. 2020) outline the ability of DAS measurements to map resonance frequencies over wide areas using the H/V method, provided that a nearby three-component velocimeter is employed to extract the Fourier amplitude spectra on the vertical component.

All the recent studies outline that DAS is a very promising technology for near-surface characterization, especially in urban environment. However, routine use of DAS data from dark fibers still needs a number of challenges to be overcome: e.g. advancements in data acquisition and data processing workflow especially to remove near-field noise or to enhance signal-to-noise ratio; positioning of channels along the DAS cable using tap tests and study of the coupling to the surrounding of the cable in conduit (Kennet et al. 2024); understanding the urban noise wavefield in relation with spatial and temporal change in anthropogenic and environmental forcings, e.g. (Fang et al. 2020) (Czarny et al. 2023).

5. Conclusions

Being cost-effective and easy to implement, especially in urban environment, passive seismic methods are reliable tools to retrieve the soil resonance frequency and the *Vs* profile of near-surface geological layers (i.e first tens to hundred of meters). However, these methods are not able to retrieve the fine *Vs* layering and to correctly constrain the depth and velocity of seismic bedrock remains a recognized challenge. Some state-of-practice and recommendations on the acquisition and processing of surface wave data have been recently proposed by the wide community to promote the use of such methods and to achieve homogeneous data analysis. Recent methodological development using single-station methods (in particular inversion of H/V curve under diffuse wavefield assumption) and three-component array methods are promising approaches to exploit at best the full complexity of the seismic noise wavefield in the view of better constraining *Vs* profiles. Very recent studies have all highlighted that the very high spatial and temporal resolution offered by the Distributed Acoustic Sensing (DAS) makes this emerging technology very appealing for near-surface site characterization, especially in urban environment thanks to the existing telecommunication infrastructure. The capabilities of such new technology certainly pave the way to exciting research dedicated to high spatial resolution imaging and monitoring of the near-surface properties.

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