Journal of Applied Geophysics 130 (2016) 37–52

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Shear wave velocity profile estimation by integrated analysis of active and passive seismic data from small aperture arrays

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ARTICLE INFO

Article history:
Received 27 February 2015
Received in revised form 24 March 2016
Accepted 29 March 2016
Available online 7 April 2016

Keywords:
Active seismic
Passive seismic
Virtual active seismic
Dispersion curves
Inversion
V_s profiles

ABSTRACT

We present an integrated approach for deriving the 1D shear wave velocity (Vs) information at few tens to hundreds of meters down to the first strong impedance contrast in typical sedimentary environments. We use multiple small aperture seismic arrays in 1D and 2D configuration to record active and passive seismic surface wave data at two selected geotechnical sites in Germany (Horstwalde & Löbnitz). Standard methods for data processing include the Multichannel Analysis of Surface Waves (MASW) method that exploits the high frequency content in the active data and the sliding window frequency–wavenumber (f–k) as well as the spatial autocorrelation (SPAC) methods that exploit the low frequency content in passive seismic data. Applied individually, each of the passive methods might be influenced by any source directivity in the noise wavefield. The advantages of active shot data (known source location) and passive microtremor (low frequency content) recording may be combined using a correlation based approach applied to the passive data in the so called Interferometric Multichannel Analysis of Surface Waves (IMASW).

In this study, we apply those methods to jointly determine and interpret the dispersion characteristics of surface waves recorded at Horstwalde and Löbnitz. The reliability of the dispersion curves is controlled by applying strict limits on the interpretable range of wavelengths in the analysis and further avoiding potentially biased phase velocity estimates from the passive f–k method by comparing to those derived from the SPatial AutoCorrelation method (SPAC). From our investigation at these two sites, the joint analysis as proposed allows mode extraction in a wide frequency range (~0.6–35 Hz at Horstwalde and ~1.5–25 Hz at Löbnitz) and consequently improves the Vs profile inversion.

To obtain the shear wave velocity profiles, we make use of a global inversion approach based on the neighborhood algorithm to invert the interpreted branches of the dispersion curves. Within the uncertainty given by the apparent spread of forward models we find that besides a well defined sediment velocity range also a reasonable minimum estimate of bedrock depth and bedrock velocity can be achieved. The Vs estimate for the best model in Horstwalde ranges from ~190 m/s at the surface up to ~390 m/s in the bottom of the soft sediment column. The bedrock starts earliest around 200 m depth and bedrock velocities are higher than 1000 m/s. In Löbnitz, we observe slightly lower velocities for the sediments (~165–375 m/s for the best model) and a minimum thickness of 75 m.

1. Introduction

Estimating the shear wave velocity (Vs) model of the shallow subsurface is of interest for application in seismic hazard assessment and geotechnical engineering (e.g. (Dobry et al., 2000; Boore and Atkinson, 2008; Bora et al., 2014, 2015). It relates to the material shear strength and is a sensitive parameter to subsurface lithological changes (see e.g. (Mainsant et al., 2012) and thus it is an important parameter for soil classification within the context of earthquake resistant building design as reported in the National Earthquake Hazards Reduction Program (NEHRP) and the Eurocode-EC8 (NEHRP, 1997; EC8, 2004).

Direct shear wave velocity measures can be obtained by laboratory determination of the shear modulus using a triaxial test on soil samples (see Bishop and Henkel, 1962 for details on the procedure). Due to loss of cohesion of soil samples during transport to laboratory (a quantification of the degree of disturbance is given in Braya, 2009), the experiment is usually complimented by in-situ tests, e.g. standard penetration test and cone penetration test (e.g Mayne, 1997; Akin et al., 2011). All of the above are only scarce in space and thus difficult to generalize or extrapolate to the whole study region.

The application of geophysical techniques, however, allows indirect estimation of shear wave velocities by inverting appropriate observation data. This includes the inversion of the dispersion characteristic of Rayleigh (and Love) waves (e.g. Horike, 1985; Tokimatsu et al., 1992; Asten and Boore, 2005; Cornou et al., 2006; Renalier et al., 2009; Dal

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http://dx.doi.org/10.1016/j.jappgeo.2016.03.034
0926-9851/

Table 1
Array geometry and parameters ranges definition for the dispersion curve analysis at the test site in Horstwalde. The recording length for each seismic experiment is reported. Derived frequency ranges from each method are reported in the last two columns.

Code/Geometry	# stat.	D_{min} (m)	D_{max} (m)	K_{min} (rad/m)	Recording length	Method	f_{min} (Hz)	f_{max} (Hz)
H09B/2D	6	13.5	31	0.20	12 h	SPAC	6	16
H10C/2D	114	3	75	0.08	1 h	SPAC	5	12
H11D/2D	8	5	34	0.18	3.5 h	SPAC	6	20
H09B/2D	6	13.5	31	0.20	12 h	Passive-fk	6	20
H10C/2D	114	3	75	0.08	1 h	Passive-fk	6	30
H11D/2D	8	5	34	0.18	3.5 h	Passive-fk	6	20
H11CGF/1D	15	165	1760	0.004	3 days/10 s	IMASW	0.6	3.4
H12A/1D	96	1	96	0.21	0.75 s	MASW	8	35

Moro and Ferigo, 2011; Puglia et al., 2011), the inversion of the Rayleigh wave ellipticity (e.g. Fäh et al., 2003; Arai and Tokimatsu, 2004) or the combined inversion of both the dispersion curve and the ellipticity (e.g. Scherbaum et al., 2003; Arai and Tokimatsu, 2005; Parolai et al., 2005; Picozzi and Albarello, 2007; Dal Moro, 2010; Hobiger et al., 2013). Here we use the dispersion characteristics of surface waves that provides the basis for estimating the average S-wave velocity profile of the underlying media through inversion assuming a simplified 1D-stratification of physical properties (e.g. Tokimatsu et al., 1992; Wathelet et al., 2004; Socco et al., 2010; Dal Moro et al., 2015). In sedimentary basins with tens to few hundreds of meters thick deposits, the determination of the Vs profile using surface waves methods then requires an accurate estimate of the phase velocity dispersion curve covering the broadest possible frequency range.

The goal of broadband dispersion curve estimation can be achieved by using arrays of increasing apertures (Woods and Lintz, 1973; Asten and Henstridge, 1984) and/or by a combined analysis of active and passive seismic data (Rix et al., 2002; Asten and Boore, 2005; Renalier et al., 2009; Renalier, 2010). A new method known as noise correlation slant-stack technique (Gouédard et al., 2008a) or Interferometric Multichannel Analysis of Surface Waves (IMASW; O'Connell and Turner, 2011) uses the advantages of the passive data (low frequency wavefield) and combines it with signal processing techniques for active data sets, hence knowing the (virtual) source position, for the dispersion curve estimation. Significant interest has been given recently by practitioners to this method (Feuvre et al., 2015; Cheng et al., 2015; Pan et al., 2016).

The combination of all methods then provides a better appraisal of the derived phase velocity dispersion curves as shown in the following. In particular, we investigate the effectiveness of the above mentioned key points (combination of active and passive seismic data, use of multi-processing methods defined in the next section) to provide a reliable dispersion estimate of the propagating surface waves for a broad frequency range.

We use a set of multi-aperture seismic arrays (1D for active & passive and 2D for passive) together with the frequency–wavenumber (f–k) technique to determine the phase velocity dispersion curve of the propagating surface waves. We assume that the recorded seismic wavefield is dominated by surface waves and of Rayleigh wave type as only data from the vertical component are used. The f–k technique is used to determine the dispersion characteristic of the propagating surface waves for active and passive seismic data sets. We refer to the f–k analysis of the active data sets with the commonly used abbreviation MASW (Multichannel Analysis of Surface Waves; (Park et al., 1999). For applying the f–k technique to the passive data sets, we will adopt "passive f–k" in continuation.

Depending on the array aperture and the interstation distance between sensors, the frequency–slowness results for a conventional passive array setup show deficiencies in resolving propagation characteristics of multiple arriving waves in certain frequency (wavelength) bands (Socco and Strobbia, 2004; Poggi and Fäh, 2010; Poggi et al., 2012). As a consequence a clear identification of the dispersion curve branches may be difficult or even not possible (Socco and Strobbia, 2004). In this case, we combine the advantages of active shot data and passive microtremor recording by using the interferometric principle (Snieder, 2004; Curtis et al., 2006; Schuster, 2009; Wapenaar et al., 2010) to estimate the Green's function equivalents from cross-correlating the ambient vibration traces between distinct receiver pairs. The resulting correlograms, assuming the equivalence between the inter-station cross-correlation time derivative pair and the Green's function (Lobkis and Weaver, 2001; Snieder, 2004) can be reordered with inter-station distance to build a virtual active experiment setup which is then processed using the MASW method. We refer to the $f-k$ analysis applied to distance sorted correlation Green's function as Interferometric-MASW (IMASW; (O'Connell and Turner, 2011). Different terminologies can also be found in the literature (Gouédard et al., 2008a; Feuvre et al., 2015; Cheng et al., 2015; Pan et al., 2016).

The IMASW approach provides a two fold advantage: a) the array response function along the denser 1D virtual receiver array shows better characteristics in terms of resolution and separation of distinct wave numbers in the wavefield; b) the IMASW exploits the frequency band of the ambient vibration wavefield that – compared to active MASW experiments – is enriched in energy at lower frequencies and thus provides the chance to estimate dispersion characteristics for longer wavelengths.

The capability of the array to separate two waves propagating at closely spaced wavelengths/wavenumbers, known as array resolution limit is estimated in the passive experiment from the shape of the respective array response function (ARF) (Woods and Lintz, 1973; Asten

Table 2
Array geometry and parameters ranges definition for the dispersion curve analysis at the test site in Löbnitz. The recording length for each survey is reported. Derived frequency ranges from each method are reported in the last two columns.

Code/Geometry	# stat.	D_{min} (m)	D_{max} (m)	k_{min} (rad/m)	Recording length	Method	f_{min} (Hz)	f_{max} (Hz)
L12P1/2D	11	62	258	0.024	20.5 h	SPAC	1.5	3.5
L12P2/2D	11	59	248	0.025	20.5 h	SPAC	1.5	3.5
L12P3/2D	11	58	243	0.026	24.5 h	SPAC	1.5	3.5
L12P1/2D	11	62	258	0.024	20.5 h	passive-fk	1.5	3.5
L12P2/2D	11	59	248	0.025	20.5 h	passive-fk	1.5	3.5
L12P3/2D	11	58	243	0.026	24.5 h	passive-fk	1.5	3.5
L12CGF/1D	165	58	258	0.024	~1 day/4 s	IMASW	1.6	8
L12A/1D	144	1	144	0.16	1.05 s	MASW	8	25