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Research paper

OpenHVSR: imaging the subsurface 2D/3D elastic properties through multiple HVSR modeling and inversion

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ABSTRACT

OpenHVSR is a computer program developed in the Matlab environment, designed for the simultaneous modeling and inversion of large Horizontal-to-Vertical Spectral Ratio (HVSR or H/V) datasets in order to construct 2D/3D subsurface models (topography included). The program is designed to provide a high level of interactive experience to the user and still to be of intuitive use. It implements several effective and established tools already present in the code ModelHVSR by Herak (2008), and many novel features such as: -confidence evaluation on lateral heterogeneity -evaluation of frequency dependent single parameter impact on the misfit function -relaxation of V_p/V_s bounds to allow for water table inclusion -a new cost function formulation which include a slope dependent term for fast matching of peaks, which greatly enhances convergence in case of low quality HVSR curves inversion -capability for the user of editing the subsurface model at any time during the inversion and capability to test the changes before acceptance. In what follows, we shall present many features of the program and we shall show its capabilities on both simulated and real data. We aim to supply a powerful tool to the scientific and professional community capable of handling large sets of HSVR curves, to retrieve the most from their microtremor data within a reduced amount of time and allowing the experienced scientist the necessary flexibility to integrate into the model their own geological knowledge of the sites under investigation. This is especially desirable now that microtremor testing has become routinely used. After testing the code over different datasets, both simulated and real, we finally decided to make it available in an open source format. The program is available by contacting the authors.

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1. Introduction

Early uses of microtremor for microzonation studies dates back to the 1950s. However, they became increasingly popular in the 90s after the paper of Nakamura (1989), who first introduced the H/V concept (i.e. the ratio between the Fourier spectra of the horizontal and vertical components of the seismic ambient noise). The use of microtremor for the estimation of the local site effects has become increasingly popular especially thanks to its simple approach which only requires the use of a single three-component seismograph and thanks to its applicability which is at present time enhanced by the availability of a wide range of low cost instruments. It is now well understood that the peaks of a HVSR curve occur at the resonance frequencies of the measurement site and are connected to the acoustic impedance contrasts in the subsurface, so that valuable information about the potential seismic amplification at sites where soft sediments resides over bedrock can be achieved by investigating the microtremors. The theoretical basis of the method still remains a matter of discussion. In the early seventies several Japanese scientists (Nogoshi and Igarashi, 1971; Shiono et al., 1979; Kobayashi, 1980) assessed the physical significance of the H/V ratio showing that there is a direct relationship with the ellipticity of Rayleigh waves. Nakamura (1989), on the other hand explained H/V peaks as caused by multiple reflections of vertically incident SH waves. Despite these different explanations, the H/V technique is now widely used for site-specific investigations and microzonation studies (Mucciarelli and Gallipoli, 2001; Scherbaum et al., 2003; Gallipoli et al., 2004a; D'Amico et al., 2008; Albarello et al., 2011). Other applications of the H/V regard the first-order estimation of the geometry of the main seismic reflector and the mapping of the sediments thickness overlying the seismic bedrock (Parolai et al., 2002; Hinzen et al., 2004; D'Amico et al., 2008). Another relevant application of microtremors, regard the identification of the fundamental frequency of buildings and the soil-structure interaction (Mucciarelli and Gallipoli, 2001; Gallipoli et al., 2004b).

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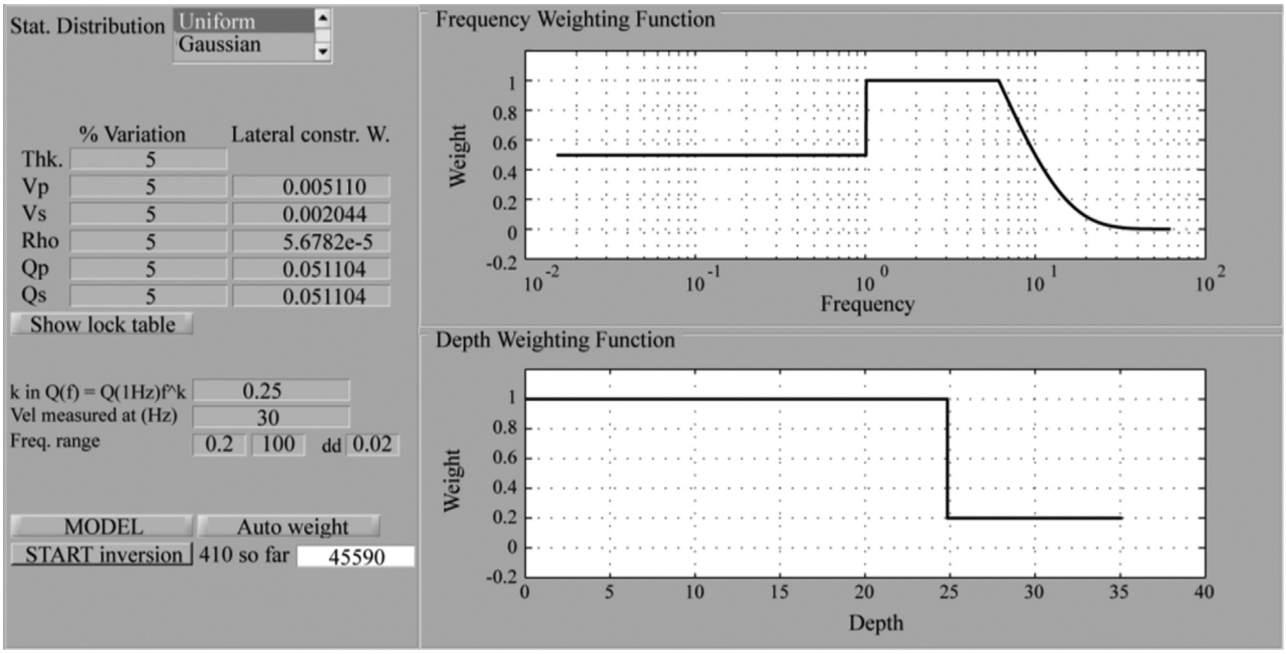

Fig. 1. View of Tab 1: modeling and inversion setup. The controls on the tab allow setting the parameters to simulate the HVSR curves at each location and to setup the inversion.

Originally based on a simple layer over half space subsurface, computational methods for the evaluation of the HVSR curve have recently become available for multi-layer systems where the subsurface is modeled as a stack of infinite homogeneous layers and using different approaches such as computation of mechanical transfer functions (Aki and Richards, 2002; Ben-Menahem and Singh, 1981; Tsai and Housner, 1970) or even exploiting the statistical approach (Sánchez-Sesma et al., 2011; Lunedei and Albarello, 2010, 2015). These modeling strategies have allowed for the investigation of the behavior of a more complex subsurface and have triggered the implementation of codes for the inversion of such curves, as for example the software Grilla (http://www.tromino.eu) or the open source Geopsy (http://geopsy.org). In 2008, Herak published ModelHVSR, a Matlab program capable of obtaining the 1D distribution of the elastic properties of a subsurface by the inversion of a HVSR curve.

After the introduction of this software, HVSR method became so popular and reliable that subsurface investigations based on multiple HVSR measurements performed at different locations started to be used for the construction of 2D subsurface images (Herak et al., 2010). At present time, the strategy behind a 2D HVSR investigation is through "HVSR-profiling", which consists of placing the HVSR curves obtained along a linear profile, back to back and translating the frequency axis into "pseudo-depth" by means of some empirical relation (e.g. $f_0 = V_s/4$ H or using a function where V_s increases with depth), which is usually based on a single and almost arbitrarily chosen average shear waves velocity (V_s) value of the top sediments. The image obtained by HVSR-profiling is only an interpretation of the informative content of the data, but it has proved to be a very useful tool to depict the 2D nature of a subsurface. The final link between this image and the true subsurface is usually provided by comparing the 2D pseudo-profile to the 1D models obtained by inverting the HVSR curves for few key locations.

Despite its usefulness, however, HVSR-profiling does not allow the retrieval of an entire true 2D subsurface profile. This is because only a single value of V_s is used in the frequency-to-depth conversion. Further, to our knowledge, there is no code available, capable of simultaneously inverting multiple HVSR curves, especially when dealing with massive HVSR surveys.

In this paper we introduce an open source program, which we named OpenHVSR, for the simultaneous modeling and/or inversion of massive HVSR datasets. The present program shares some similarities to Herak's ModelHVSR and actually, some of those tools were integrated into the present implementation. This program was especially designed to obtain the 2D and 3D subsurface distribution of the viscoelastic parameters by the inversion of massive HVSR datasets rather than investigating one site at a time. Furthermore, it was designed to give the user the maximum interactivity and dynamicity during the inversion process. Finally, a set of new tools and relevant inversion improvements were implemented.

In what follows, we describe the structure of the program and its capabilities. We shall show an example of inversion of data simulated on a linear array over a subsurface model with lateral variation and finally, we shall illustrate an example of inversion of real data where the depth of the major acoustic impedance contrast (i.e., the so called pseudo-bedrock) was retrieved and where the reconstructed geometry was found in good accordance both with a seismic reflection survey (Fantoni and Franciosi, 2008) running parallel to a portion of our HVSR profile and with other shallow geological information (RER and ENI-AGIP, 1998).

2. Algorithm and optimization strategy

The algorithm is composed of several routines integrated into a main graphical user interface (GUI), which is organized in tabs. The input consists of a text project file which specifies the field geometry (i.e. locations of measurements, including elevation), data path and filenames and one or more files to define an initial subsurface model under the measurement locations. To assure maximum compatibility with commercial acquisition instruments, almost any data file structure is loadable with minimum intervention, provided it is an ASCII format. The subsurface under each measurement site is assumed to be locally layered and the initial subsurface model can be supplied using one or multiple files to

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