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Integrated Workflow for Surface-wave Dispersion Inversion and Profiling

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SUMMARY

While surface-wave prospecting methods are classically applied for the one-dimensional (1D) estimation of shear (S-) wave velocities (Vs), two-dimensional (2D) profiling still requires implementing specific processing and inversion tools that are not yet widely available in the community. We present here a free and open-source tool performing surface-wave inversion and profiling (SWIP) in order to retrieve 2D lateral variations of Vs from typical seismic shot records. Windowing and stacking techniques are implemented to compute dispersion images with smooth lateral variations and enhanced signal-to-noise ratio. Dispersion curves are extracted for each window with an error in phase velocity taking into account the higher uncertainties at low frequency. These curves are then inverted for each window position using a Monte Carlo approach and a refraction tomography-based parameterization. Models matching the observed data within the error bars are selected to build a misfit-weighted final model and estimate the investigation depth. Finally, 1D models obtained for each window position are merged into a 2D Vs section.

Introduction

In near-surface applications (at depth lower than 100 m), seismic methods are classically used for engineering or hydrogeological purposes in order to determine the main mechanical properties of the subsurface. The joint estimation of pressure (P-) and shear (S-) wave velocities (V_P and V_S, respectively), and the derived V_P /V_S and Poisson's ratios, has recently been proposed for these applications, taking advantage of the strong decoupling of these velocities with varying porosity and fluid content (liquid or gas) in the studied medium (Pasquet et al., 2015a, b).

For these shallow-target studies, V_P is generally retrieved thanks to P-wave refraction tomography using a classical plate and hammer source with vertical component geophones. P-wave refraction methods usually consist in interpreting first arrival times observed on the recorded wavefield. For that purpose, the medium is discretized in a velocity grid through which raytracing is performed. Following an iterative process, modeled traveltimes are compared to observed data, adjusting the velocity-model until a "satisfying" fit is reached. The use of this method is widespread since it is easily carried out with a one-dimensional (1D) to three-dimensional (3D) coverage, quick to implement and relatively inexpensive. However, when applied for V_S estimation, it requires a second acquisition, using horizontal component geophones difficult to set up horizontally and specific sources strenuous to handle.

As an alternative, surface-wave prospecting methods are classically applied to achieve indirect estimation of V_S using typical vertical component seismic data (Socco et al., 2010). The recorded wavefield is basically transformed to the frequency-wavenumber (or frequency-slowness) domain in which maxima correspond to different surface-wave propagation modes (theoretically related to the shear properties of the medium). When propagation modes are well separated on these dispersion images, several dispersion curves can be picked and inverted for a 1D V_S profile with depth. If the 1D estimation of V_S is now performed in a relative straightforward manner, two-dimensional (2D) profiling still requires implementing specific processing and inversion tools that are not yet widely available in the community. Furthermore, intrinsic limitations of the method when applied for 2D profiling (i.e. 1D inverse problem formulation leading to a delicate trade-off between depth of investigation and lateral resolution) can easily lead to over interpretation of the results.

We present here a MATLAB-based, free and open-source tool (available upon request by contacting the first author) performing surface-wave dispersion inversion and profiling (SWIP) in order to retrieve 2D lateral variations of V_S from typical seismic shot records. After a description of the processing and inversion methodology, we present an example using real field data.

Extraction of dispersion curves

SWIP takes advantage of multi-shot acquisition set-ups to retrieve the lateral variations of surface-wave (i.e. Rayleigh or Love depending on the source and geophone component) dispersion using shot gather windowing and dispersion stacking (data-handling is achieved thanks to the open software package Seismic Unix). A range of acceptable window sizes and shot offsets is first defined to extract the data (Neducza, 2007) and compute dispersion images using a slant stack in the frequency domain (p-ω stack, Mokhtar et al., 1988). The window size is a key parameter that needs to be defined with care based on the desired lateral resolution and investigation depth. In the one hand, the window has to be short enough to validate the 1D hypothesis (i.e. no or only small lateral variations below the extraction window) required for the inverse problem, while in the other hand it has to be large enough to ensure sufficient spectral resolution in order to record low frequency dispersion data and increase the investigation depth.

The windows are then shifted along the acquisition profile to obtain a set of dispersion images associated with their corresponding spread mid-point (*Xmid*). Dispersion images associated with an identical *Xmid* are finally stacked to improve signal-to-noise ratio and enhance the maxima (O'Neill et al., 2003). The shift between two successive extraction windows can range from one receiver spacing to several window lengths, depending on the expected lateral variations in the studied medium. Using a large overlap allows retrieving smoothly varying dispersion images between two adjacent stacking windows and help for visual browsing when picking dispersion curves.

On each stacked dispersion image, the coherent maxima associated with the different propagation modes are identified, picked and extracted with an estimated standard error in phase velocity depending on the frequency and the spread length so as to reduce possible low-frequency discrepancies (O'Neill, 2003). The dispersion curves can then be resampled either in wavelength or in frequency, with several criterions limiting their frequency range into reasonable boundaries (e.g. minimum frequency defined according to the spectral amplitude, maximum wavelength defined according to the extraction window length…). A discretization in wavelength is generally recommended in order to invert depth consistent data. This also prevent from giving excessive weight to high frequency samples which correspond only to the shallowest part of the medium.

Inversion of dispersion curves

Assuming a 1D tabular medium below each extraction window, SWIP performs 1D inversion of dispersion data obtained at each *Xmid* position. We assume that stacking and windowing laterally smooth and constrain the dispersion data, thus not requiring the use of lateral constraints between successive inversions. Theoretical dispersion curves are computed from the elastic parameters using the Thomson–Haskell matrix propagator technique as implemented by Dunkin (1965). The inversion is completed with the neighborhood algorithm (NA) implemented for near-surface applications by Wathelet et al. (2004) within the open software package Geopsy. The NA performs a stochastic search of a pre-defined parameter space (namely V_P, V_S, density and thickness of each layer) using the misfit function defined in Wathelet et al. (2004).

The parameterization can include several layers, with fixed or varying thickness, velocity and density. Velocities can be defined in each layer with various depth-dependent shapes (uniform, linear increase or decrease, power law…) allowing a large range of possible models. V_P being of weak constraint on surface-wave dispersion, only V_S can be interpreted. However, an identical layering should be used for V_P and V_S in order to interpret variations of V_P /V_S or Poisson's ratio (Pasquet et al., 2015b). For this purpose, SWIP offers to create a semi-automatic parameterization based on the results of P-wave refraction tomography. V_P soundings are extracted at each *Xmid* position from the tomography model and resampled according to the desired parameter space discretization in depth. This average value can then be used to fix V_P in each layer or to estimate a limited and realistic variation range. As for density, it can usually be set as uniform since its influence on dispersion curves is very weak.

Thousands of models can be generated for each *Xmid* with the NA, allowing the appraisal of an *a posteriori* estimate of the model error. Several options are proposed to build the final 1D V_S model: (i) using the model with the lowest misfit; (ii) using an average of the *n* models with the lowest misfits; (iii) or using an average of all models whose calculated dispersion curves fit the observed data within the error bars. In the two latter cases, the final average model can be constructed either by taking the actual mean value of each parameter, or by weighting the different parameters according to each model's misfit.

Each final 1D V_S model is then represented at its corresponding *Xmid* position to obtain a pseudo-2D V_S section. In most of the surface-wave studies presented recently, the investigation depth of 1D V_S models is usually considered as equal to the half of the maximum observed wavelength (when it is not completely ignored). To tackle such issue, we propose here to estimate the investigation depth thanks to the velocity standard deviation of all generated models with the NA. For each final 1D V_S model, we thus define the depth of investigation when the standard deviation reaches a user-defined value above which the final 1D V_S model is considered unconstrained.

Field example at the Blair Wallis site

A seismic acquisition was performed in the Blair Wallis site, located in the Laramie Range at around 20 km southeast of Laramie, Wyoming. Geophysical measurements are carried out in this site to characterize the different units composing the deep critical zone (i.e. protolith, weathered bedrock, and saprolite) in the granitic bedrock shaping the area. Seismic data were collected using four 24-channel Geometrics Geode seismographs with 10-Hz vertical component geophones spaced every 2.5 m. 28 shot gathers were recorded every 10 m using a 4.5-kg sledgehammer swung onto an aluminum plate.

Surface-wave inversion and profiling was achieved using a 10-trace window (22.5 m) with shot-window offsets ranging between 0 and 15 m (Figure 1). Dispersion images were computed for each of the windowed shot gathers and finally stacked together. The window was then shifted of 2.5 m along the acquisition profile, so as to obtain 87 stacked dispersion images. Picked dispersion curves extracted from each stacked dispersion image were finally inverted using a parameterization based on P-wave refraction tomography results. We used a stack of ten layers overlaying the half-space to look for a velocity gradient, with each layer thickness allowed for ranging between 0.5 to 2.5 m. The valid parameter range for sampling velocities was 10 m/s–2500 m/s for V_S (the V_P range being defined by tomography results), with velocities constrained to only increase with depth. A total of 56550 models were generated with the NA for each *Xmid* position. Models matching the observed data within the error bars were selected to build a misfit-weighted final model and estimate the investigation depth.

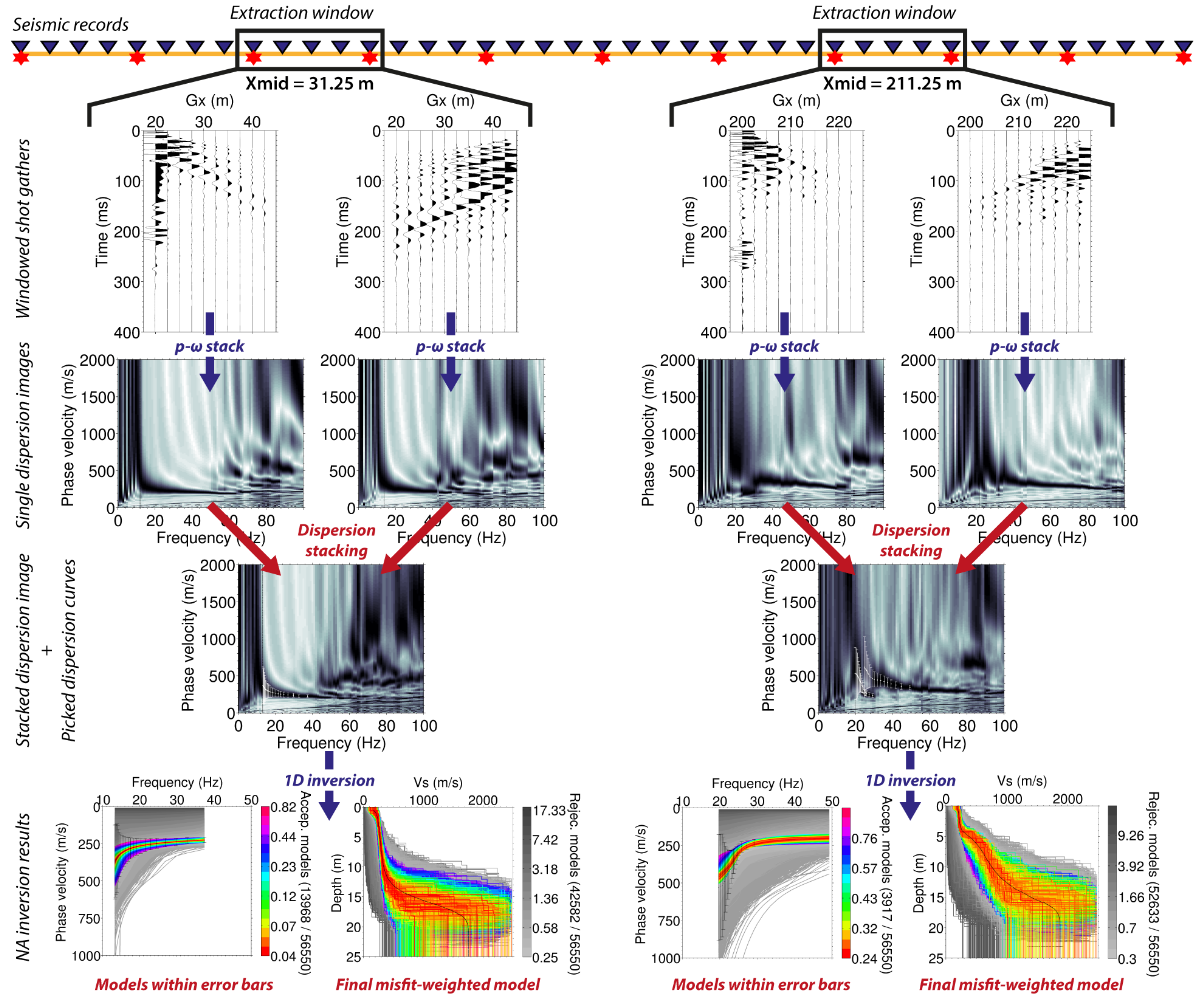

Figure 1 *Surface-wave inversion and profiling workflow illustrated by two examples at both sides of the acquisition profile (left: Xmid=31.25 m; right: Xmid=211.25 m).*

Each 1D V_S model was finally represented at its corresponding *Xmid* position to build a 2D V_S model (Figure 2a), with an estimated investigation depth delineated with a black dashed line. The V_S model appears to be remarkably consistent with the V_P model (Figure 2b) obtained after inverting the picked first arrival times using a MATLAB traveltime tomography code (St. Clair, 2015).

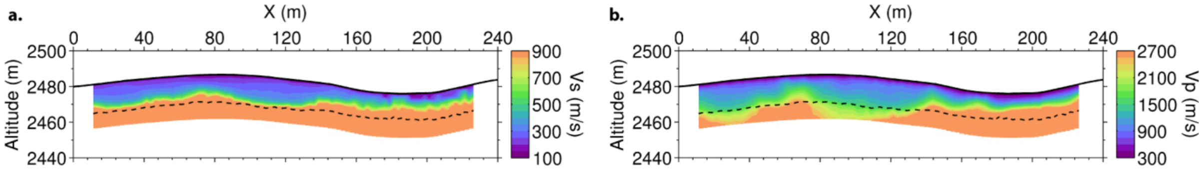

Figure 2 *(a) 2D V_S model obtained with SWIP at Blair Wallis. (b) 2D V_P model obtained with traveltime tomography. Black dashed lines correspond to the estimated investigation depth of V_S.*

Conclusions

We present here a free and open-source tool performing surface-wave inversion and profiling (SWIP) using typical seismic data. Windowing and stacking techniques are used to compute dispersion images with smooth lateral variations and enhanced signal-to-noise ratio. Dispersion curves are extracted for each window with phase velocity error taking into account the higher low-frequency uncertainties. These curves are then inverted for each window position using a Monte Carlo approach and a tomography-based parameterization. Models matching the observed data within the error bars are selected to build a misfit-weighted final model and estimate the investigation depth. 1D models obtained for each window are ultimately merged into a 2D V_S section. In the example provided here, the V_S model is in very good agreement with the V_P model obtained from traveltime tomography.

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