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Challenges for 2-D elastic Full Aaveform Inversion of Shallow-seismic Rayleigh Waves

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SUMMARY

Shallow-seismic Rayleigh waves are attractive for geotechnical site investigations. They exhibit a high signal to noise ratio in field data recordings and have a high sensitivity to the S-wave velocity, an important lithological and geotechnical parameter to characterize the very shallow subsurface.

In recent years we studied the applicability of the two-dimensional elastic FWI method using numerous synthetic reconstruction tests and two field data examples. Some important challenges are reported here: (1) the accurate correction of the geometrical spreading, (2) the estimation of the source wavelet, (3) the importance of an-elastic attenuation in the forward simulations.

We found that Important pre-processing steps for the application of 2-D elastic FWI to shallow-seismic field data are the 3D to 2D correction of geometrical spreading and the estimation of a priori Q-values that must be used as a passive medium parameter during the FWI. Furthermore, a source-wavelet correction filter should be applied during the FWI process. Smooth initial models obtained from the analysis of the first arrivals of body waves are important and seem to be sufficient. Our field data examples indicate that FWI is able to resolve lateral variations of S-wave velocities in the very shallow subsurface.

Introduction

Shallow-seismic Rayleigh waves are attractive for geotechnical site investigations. They exhibit a high signal to noise ratio in field data recordings and have a high sensitivity to the S-wave velocity, an important lithological and geotechnical parameter to characterize the very shallow subsurface. Established inversion methods assume (local) 1-D subsurface models, and allow the reconstruction of the S-wave velocity as a function of depth by inverting the dispersion properties of the Rayleigh waves. These classical methods, however, fail if significant lateral variations of medium properties are present. Then the full waveform inversion (FWI) of the elastic wave field seems to be the only solution. In addition, FWI seems to have the potential to recover consistent multi-parameter models of S-wave velocity, P-wave velocity, mass density, and attenuation, which would allow for an improved characterization oft the in-situ pore scale sediment properties.

In recent years we studied the applicability of the two-dimensional elastic FWI method using numerous synthetic reconstruction tests and two field data examples. Some important challenges are reported here: (1) the accurate correction of the geometrical spreading from 3D (field data) to 2D (simulated data), (2) the estimation of the source wavelet, (3) the importance of an-elastic attenuation in the forward simulations. The challenges of FWI of shallow seismic Rayleigh waves are further illustrated with synthetic and two field data examples.

FWI Method

Our 2-D elastic FWI is a conjugate-gradient method where the gradient of the misfit function is calculated by the time-domain adjoint method. The viscoelastic forward modelling is performed with a classical staggered-grid 2-D finite-difference forward solver. Viscoelastic damping is implemented in the time-domain by a generalized standard linear solid. As misfit definition we generally use the L2 norm of the normalized wave fields where each trace is normalized by its RMS amplitude. We use a multi-scale inversion approach by applying frequency filtering in the inversion. We start with the lowest frequency oft the field data and increase the upper corner frequency sequentially. Our modelling and FWI software is freely available under the terms of GNU GPL on www.opentoast.de.

Geometrical spreading correction

Our 3D/2D transformation is assuming acoustic wave propagation. Each seismogram is convolved with $1/\sqrt{t}$. Afterwards the traces are tapered by $1/\sqrt{t}$ and scaled by the offset multiplied with $\sqrt{2}$ where t is the travel time. The transformation produces a phase shift of $\pi/4$ as well as an amplitude scaling. Synthetic tests have shown that this single-trace method corrects the geometrical spreading of Rayleigh waves quite accurately (Forbriger et al., submitted; Schäfer et al., submitted).

Source-wavelet correction

In an inversion of field data the unknown source wavelet for each shot must be estimated. We do this at the beginning of each frequency bandwidth by a stabilized deconvolution of the recorded data with the simulated data for the current subsurface model. The source wavelets are then used unaltered within this frequency band (Groos et al., submitted).

Influence of attenuation

Attenuation in the shallow subsurface is significant. It results in a low-pass effect as well as frequency dependent decay with offset. FWI using purely elastic simulation of waves fails in reconstruction tests in the presence of attenuation. To overcome this, a priori Q values are estimated from the recordings.
Viscoelastic simulation in the FWI then uses these a priori values. Furthermore, a source-wavelet correction can compensate a significant fraction of the residuals between elastically and viscoelastically simulated data by narrowing the signals' bandwidth. With these two steps, a source-wavelet correction and using a priori Q-values as passive parameter, elastic FWI becomes applicable to viscoelastic data (Gross, 2013; Groos et al., submitted).

Field data examples

We evaluate the applicability of the 2-D elastic FWI method to two field data sets acquired with a conventional acquisition geometry: linear profiles with vertical geophones (eigenfrequency of 4.5 Hz) and equidistant receiver spacing of 1 meter. The source is a vertical hammer blow. The first data example was acquired on a test site at Rheinstetten near Karlsruhe (Germany) above a predominantly depth dependent structure consisting of fluviatile sediments. In the second example the seismic profile crosses a vertical fault system of the southern rim of the Taunus (near Frankfurt on the Main, Hesse, Germany).

Field data example I
The initial 1-D P-wave velocity model was obtained from the analysis of first arrival P-wave travel times. As initial S-wave velocity model we use a 1D linear gradient. We only invert for the S-wave velocity and P-wave velocity up to a depth of approximately 6 meter. The data misfit is successfully decreased by FWI. The final S-wave velocity model still corresponds to a predominantly depth dependent structure. The final model obtained by FWI is in a good agreement with a 1-D model obtained by the inversion of the Rayleigh-wave dispersion expressed by Fourier-Bessel expansion coefficients (Groos, 2013).

Field data example II
In our second field data set we observe a significant change in the wave field and the phase velocities along the profile that indicate significant lateral variations in the shallow subsurface. With additional seismic profiles parallel and one perpendicular to the fault we verified the assumption of a predominantly 2-D subsurface structure. The initial P-wave and S-wave velocity models up to 40 meter depth were derived from a travel-time tomography of the first arrivals of P-waves and S-waves, respectively. The FWI can successfully reduce the misfit between the field data and synthetic data up to frequencies of about 50 Hz but fails at higher frequencies. Possible reasons are non-linearities of the misfit function at higher frequencies and/or unknown small-scale medium heterogeneities that violate our 2-D assumption.

Conclusions

Important pre-processing steps for the application of 2-D elastic FWI to shallow-seismic field data are the 3D to 2D correction of geometrical spreading and the estimation of a priori Q-values that must be used as a passive medium parameter during the FWI. Furthermore, a source-wavelet correction filter should be applied during the FWI process. Smooth initial models obtained from the analysis of the first arrivals of body waves are important and seem to be sufficient. Our field data examples indicate that FWI is able to resolve lateral variations of S-wave velocities in the very shallow subsurface.

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