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Near-surface characterization in 3D complex land seismic exploration

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Summary

Surface waves are commonly regarded as undesirable noise in exploration seismology and are therefore routinely attenuated during data processing. However, these wave types are highly sensitive to shallow subsurface properties and can be exploited for near-surface characterization when properly analyzed. In complex geological settings, such as foothill regions, their interpretation is challenged by strong scattering from small-scale heterogeneities and by spatial aliasing associated with irregular and coarse acquisition geometries. In this study, we propose a workflow that leverages surface waves recorded in 3D land seismic surveys to estimate near-surface S-wave velocity variations. The workflow focuses on enhancing the stability and interpretability of surface-wave dispersion information through a combination of 3D beamforming, topographic corrections, azimuthal binning, and midpoint stacking. Dispersion images of surface waves are processed and subsequently inverted to obtain a pseudo-3D S-wave velocity model. Results from a field dataset acquired in the Colombian Foothills indicate that the proposed approach provides a consistent and geologically meaningful representation of near-surface velocity structure, facilitating improved seismic energy coupling and offering a practical input model for subsequent imaging and inversion workflows targeting deeper structures.

Workflow

Surface-wave dispersion analysis has been shown to provide a viable means of estimating near-surface S-wave velocity profiles from exploration seismic data, despite such data not being specifically designed for surface-wave studies (Socco et al., 2010; Strobbia et al., 2011; Boiero et al., 2013). However, in 3D land seismic surveys, the applicability of dispersion-based methods is often limited by irregular acquisition geometries, coarse spatial sampling (particularly in the crossline direction) and strong lateral heterogeneity, all of which complicate the extraction of stable and interpretable surface waves dispersion curves. Due to these limitations, we propose a workflow designed to improve the robustness of dispersion curve estimation by organizing the wavefield into source-azimuth gathers, applying 3D beamforming, and performing coherent stacking prior to inversion. An overview of the complete processing and inversion sequence is shown in Figure 1.

The workflow starts by using the full 3D acquisition geometry, including source and receiver coordinates and surface elevation. Given the strong topographic variations typical of foothill environments, true source–receiver geodesic distances are computed along the surface rather than assuming horizontal offsets. These geodesic distances are used throughout the analysis to correctly represent wave propagation paths and to minimize distortions introduced by rugged terrain.

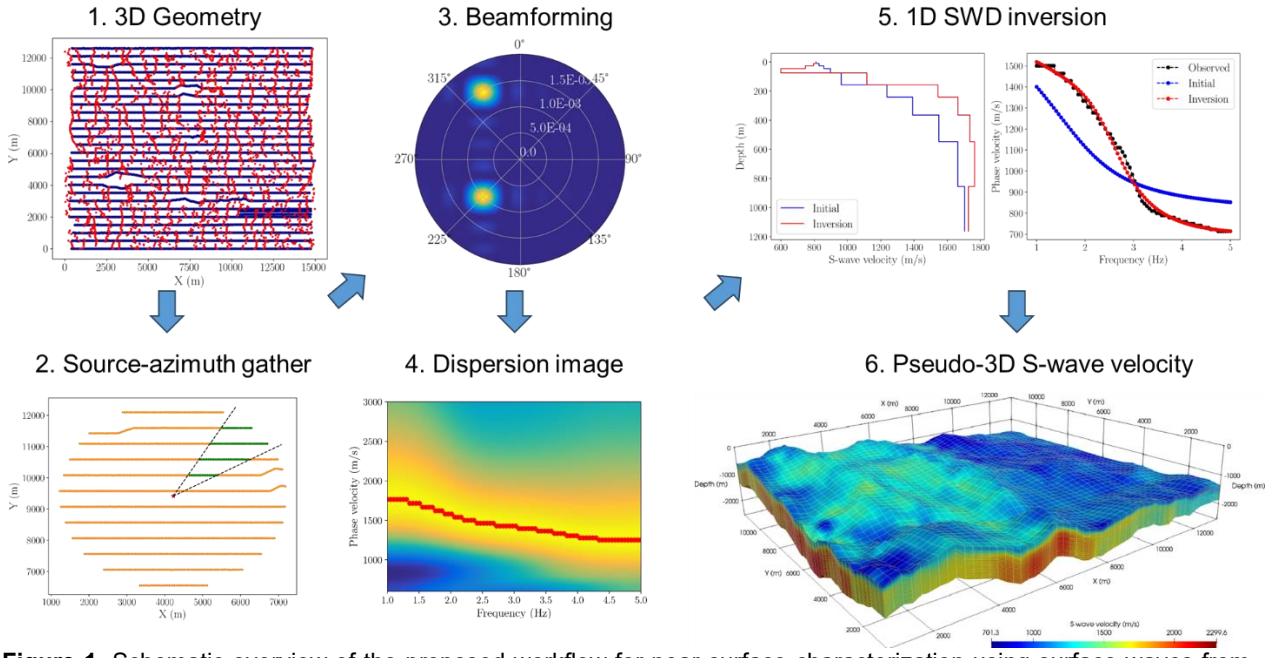


Figure 1. Schematic overview of the proposed workflow for near-surface characterization using surface waves from 3D land seismic data, showing the main processing and inversion stages from acquisition geometry handling to the construction of a pseudo-3D S-wave velocity model.

For each shot gather, receiver traces are grouped according to their azimuth relative to the source location. The data are partitioned into discrete azimuth sectors, forming source-azimuth gathers that isolate surface wave energy propagating in similar directions. This directional sorting reduces interference from waves traveling along different paths and provides a controlled framework for analyzing azimuth-dependent propagation effects. Traces within each azimuth sector are sorted by geodesic distance to form consistent gathers suitable for beamforming.

Each source-azimuth gather is processed using 3D beamforming implemented through a frequency-domain linear Radon transform. This step decomposes the recorded wavefield into plane-wave components characterized by slowness and propagation direction. Beamforming enhances coherent surface wave energy while suppressing incoherent noise and scattered contributions (Ritzwoller et al., 2002; Jin and Gaherty, 2015). Anti-aliasing masks are applied in the slowness–azimuth domain to mitigate spatial aliasing effects, particularly those arising from coarse crossline receiver spacing.

Beamforming results are mapped into the frequency–slowness domain to construct dispersion images for each azimuth sector. These images represent the distribution of surface wave energy as a function of frequency and phase velocity. To improve stability and reduce fluctuations, dispersion images associated with nearby receiver midpoints are combined through stacking. Smoothing is applied where necessary to enhance the continuity of dispersion trends and facilitate reliable curve extraction.

From the stacked dispersion images, fundamental-mode surface wave dispersion curves are extracted and inverted independently at each spatial location. The inversion is performed in a

one-dimensional framework, yielding local S-wave velocity profiles as a function of depth. Layer thicknesses are estimated based on the frequency-dependent depth sensitivity of surface waves, ensuring that each inverted profile reflects the resolving power of the available data (Xia et al., 1999).

The final pseudo-3D S-wave velocity model is constructed by spatially interpolating the ensemble of 1D inverted profiles across the survey area. Although each profile is derived independently, their combination produces a laterally varying S-wave velocity volume that captures the near-surface heterogeneities. This model provides a practical representation of near-surface velocity structure that can be used to improve seismic energy coupling, support statics and imaging workflows, and serve as an input model for subsequent inversion or imaging methods.

Results

The proposed workflow was applied to a 3D land seismic dataset acquired in the Colombian Foothills, where strong topography and near-surface heterogeneity are present. Figure 2a and Figure 2b show a representative example in which geodesic source–receiver paths are used to construct a source-azimuth gather for a selected source and azimuth sector. Using geodesic distances and azimuth-based sorting improves phase alignment of surface-wave arrivals, which in turn stabilizes the estimation of dispersion curves, even in the presence of irregular acquisition geometry and coarse spatial sampling.

The inverted dispersion curves are interpolated to produce a spatially coherent pseudo-3D S-wave velocity model that captures strong lateral and vertical variations in the shallow subsurface. The resulting velocity distribution, illustrated in Figure 2c and Figure 2d, follows expected near-surface trends and exhibits smooth transitions between adjacent areas, indicating that the model is controlled by coherent dispersion information rather than local artifacts. These results demonstrate that surface waves from conventional 3D land seismic data can be exploited to derive meaningful near-surface S-wave velocity models in complex terrain.

Conclusions

This work shows that the proposed workflow can exploit surface waves recorded in complex 3D land seismic data to obtain reliable near-surface S-wave velocity models. The workflow improves the extraction of surface-wave dispersion curves by accounting for topographic elevation through geodesic source-receiver distances, organizing the data by propagation direction using source-azimuth binning, and applying coherent stacking prior to inversion. These steps allow stable dispersion curves to be obtained despite irregular acquisition geometry and coarse spatial sampling. Inversion of the dispersion curves yields spatially consistent one-dimensional S-wave velocity profiles that are interpolated to construct a pseudo-3D near-surface velocity model capturing significant lateral and vertical variations. The resulting model provides a practical representation of near-surface complexity in foothill environments and can be directly used to support seismic processing and imaging workflows that require improved near-surface velocity models.

Acknowledgements

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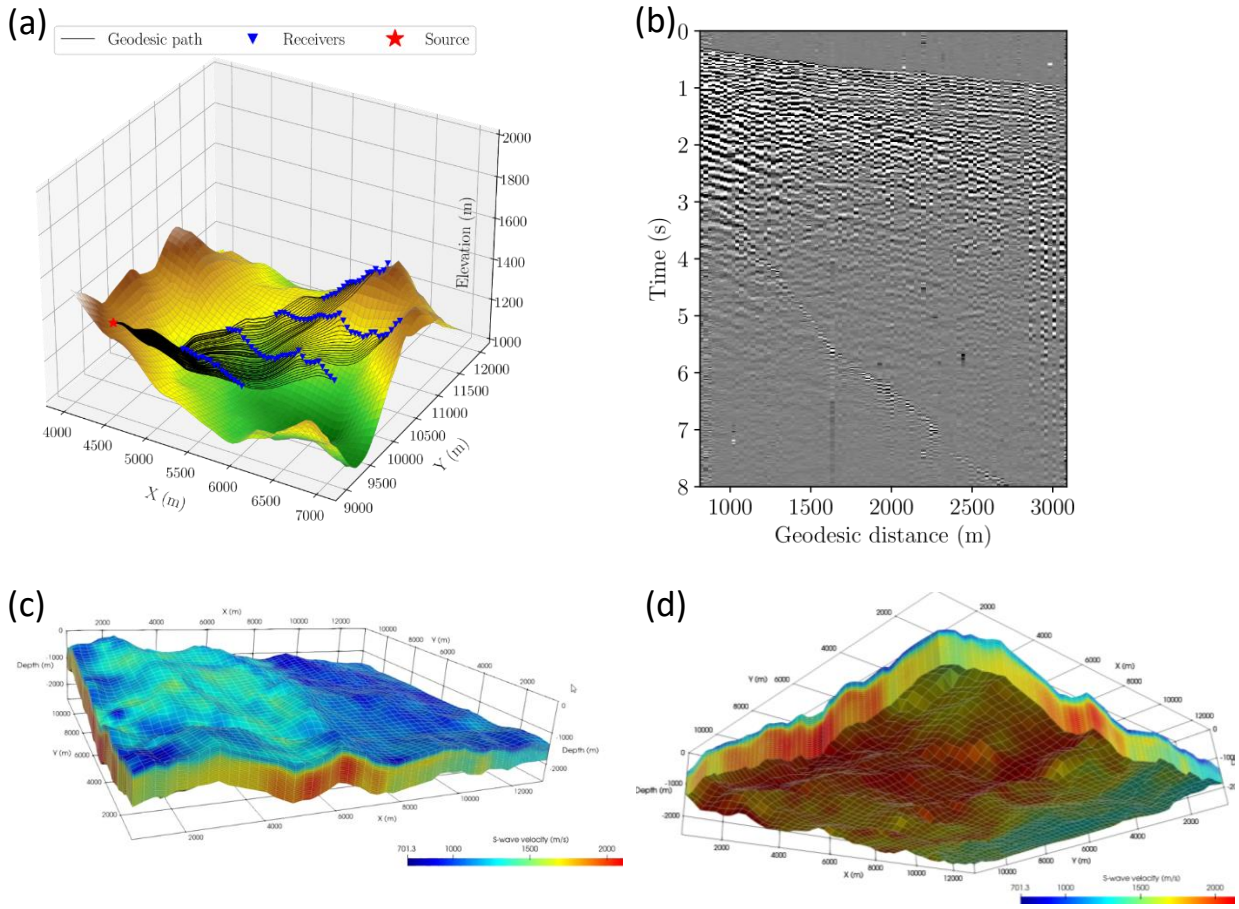


Figure 2. Representative results obtained from the application of the workflow. (a) Geodesic paths between the source and receivers within a selected azimuth sector. (b) Corresponding source-azimuth gather sorted by geodesic distance. (c) Top view and (d) bottom view of the pseudo-3D near-surface S-wave velocity model constructed by interpolating multiple one-dimensional inverted profiles.

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