Near-surface characterization, challenges, and solutions for high-density, high-productivity, broadband vibroseis point-source and receiver survey – a case study

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Summary

We present the results of the near-surface characterization for a 3D survey in thrust belt area in Sharjah, United Arab Emirates.

The near surface is very complex, with steeply dipping layers, faults, extreme lateral and vertical velocity variations, and vertical velocity inversions: all these features challenge conventional, refraction-based seismic methods.

Surface-wave analysis and inversion provide a geologically consistent near-surface velocity model. Integration and validation of the model using other near-surface data, such as analysis of refractions and upholes, is presented along with a workflow for integrating near-surface measurements and statics computation.

The shallow earth model, besides being used for the near-surface perturbation corrections, is interpreted together with other measurements.

We show that the near-surface complexity is not only a cause of distortions and perturbations in the deep seismic images. The near-surface characterization can provide geologically consistent models, with high spatial resolution to identify structural and lithological elements of the near surface, which can be used for geological modeling and in general exploration.

Introduction

The shallow portion of the subsurface has a dramatic impact on geophysical data. The so-called near surface is often characterized by large variations of the physical properties due to weathering, differential compaction of sediments, and structural and stratigraphic features, adding further complexity.

Near-surface characterization is an important step in seismic data processing for generation of high-fidelity undistorted images and extraction of reliable subsurface attributes. A set of conventional, usually refraction-based, characterization methods are typically used for characterization of the near-surface: these methods, however, rely on some assumptions on the velocity distribution, and can struggle in the presence of complex velocity models.

Other approaches, based on analysis of surface waves, are gaining popularity because of their robustness and ability to overcome the intrinsic limitations of conventional techniques. Surface waves are high-energy events that tend to dominate the offset ranges where they are recorded. They have a high signal-to-noise ratio, and it is often easier and more reliable to analyze surface-wave dispersion rather than picking the first-break traveltimes. Despite the possible challenges due to their multimodal nature, integrated surface measurements can solve complex velocity structures with velocity inversion and sharp velocity variations: at the scale of seismic reflection prospecting, they allow resolution of large lateral variations.

The availability of these alternative tools for near-surface characterization can turn the near-surface complexity from a challenge into an opportunity. In fact, complex near-surface geology poses challenges to conventional geophysical methods, but at the same time, it also exposes valuable geological information. Identification of structural elements in the near surface can help geological modeling and interpretation.

How such complexity influenced a solution for the near-surface characterization is illustrated using a case study for a 3D thrust-belt area survey acquired in the 3rd quarter of 2011. On an area of about 229 km$^2$, a full-azimuth three-dimensional seismic survey was acquired with a high-productivity single-sensor system (Van Baaren et al., 2012).

This exploration play extends from the United Arab Emirates through to Oman, where the prolific stable Arabian plate was deformed by the Late Cretaceous orogeny, resulting in structurally controlled traps. Further compressional deformation occurred in the Miocene to Oligocene with the collision of Arabia and Eurasia. Typically, the imaging task in thrust belt regions is challenging due to the complex raypaths and steeply dipping events. In addition, the near surface is covered by an inhomogeneous sand layer. The concession surface consists of sand dunes ranging from a few to 100 m and a few rock outcrops, but no clear evidence of structural elements appears at the surface despite the expected geological complexity.
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In this context, the near-surface geophysical properties have large variability along the vertical and horizontal direction: this induces large perturbations in the surface geophysical data. In particular, the near-surface perturbations produce time delays, waveform distortion, and absorption in seismic data. The spatial variability of the travelt ime through the near surface can be compensated in conventional time-imaging with the application of static corrections (Cox et al., 1999) or used directly at the depth-imaging stage.

The near-surface characterization was performed integrating different data and measurements with calibration and validation of the results of the surface-wave analysis and inversion.

Surface-wave analysis and inversion in complex near surface

The application of surface-wave methods, already in use in global seismology and engineering, to reflection 3D data can exploit some of the properties of modern land data, and become a tool for near-surface characterization.

Surface waves are an important component of all land seismic data. A large part of the source energy propagates as surface waves (ground roll) that dominate gathers in the near- and mid-offset range—often up to the offset where they are recorded.

Surface-wave analysis and inversion gives optimal results with point-receiver broadband data. Low-frequency sources and receivers allow better recording of the long wavelengths, which is important to enable a larger investigation depth. Point-receiver acquisition and denser spacing, without field analogue arrays, allows recording surface waves without distortion in the short-wavelength range. A factor of great importance in dealing with a complex near surface with high variability and noisy data is the extreme redundancy of the surface-wave sampling—the surface-wave fold, i.e., the number of traces that can be used for the surface-wave analysis for a specific surface location. In this respect, dense macro geometry was an important element, not only for sampling the reflection signal, but also for a robust implementation of surface-wave analysis.

The procedure for surface-wave characterization consists of two steps: first, analysis of the raw data extracts the surface-wave propagation properties, which are then inverted into a near-surface geophysical model as a second step.

In particular, the adopted approach consists of 1) estimation of a 3D volume of surface-consistent phase velocities properties: the phase velocity of Rayleigh wave modes as a function of surface coordinates and frequency or wavelength, and 2) inverting the dispersion into a shear-wave velocity volume.

The quality of the dispersion estimation is crucial for reliable near-surface modelling; it depends on the presence of well-developed and coherent surface waves, but also on the data spatial sampling—the total number of traces from shots and receivers within the optimal range of offset and azimuth for surface-wave analysis. The analysis extracts the local properties, gathering traces over a limited physical aperture to identify lateral variations with high lateral resolution: the local supergathers can contain tens of thousands of traces over a short aperture. The robustness of the workflow comes from the optimal use of the large redundancy of dense macro geometries: an optimal subset of data is selected, considering the frequency and offset dependence of the signal-to-noise ratio, lateral resolution, spectral resolution, and near-field effects. More details are given by Strobbia et al. (2011).

Identification of surface-wave properties aims at extracting the dispersion, even in presence of spatial aliasing, scattering, and large lateral variations.

Dataset indeed show lateral variations and scattering and extreme variations of the velocity, frequency, and offset ranges. Multiple modes are present, and due to the near-surface complexity, in some areas, surface waves do not look very coherent in gathers. Strong incoherent noise is also present, and it is more evident in single-sensor data.

The data challenges in the area are compensated by a dense sampling of the surface-wave wavefield. The acquisition geometry consists of 200-m spaced source and receiver lines, and 12.5-m source and receiver spacing, providing an ideal sampling of the surface waves.

An example of analysis is shown in Figure 1. On the left, a shot gather with aliased surface waves with scattering is shown. A standard f-k spectrum is shown in the middle panel, and the spectrum of the local supergather is shown in the right panel. The spectrum is computed over a small surface bin, whose extent is indicated by the blue box that, however, contains more than 40,000 traces. The presence of two modes, up to a wavenumber exceeding twice the Nyquist is identified.

Near-surface velocity model from seismic waveform inversion

Surface-wave analysis is performed by processing selected (in offset and azimuth) raw data for all the receiver lines. With a final average surface-wave fold of over 2000, the
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dispersion analysis can be done consistently for the entire survey. The dispersion volume is then inverted to get a shear-wave velocity volume. The investigation depth, in general, is controlled by the longest wavelength: in SOCD3, a low-frequency sweep (3.5-64 Hz) produces an investigation depth that consistently reaches 100 m from the surface.

Steeply dipping layers, large lateral variations, and velocity inversions are obtained. Due to the rapid variations of the near-surface velocities, the analysis was run to extract the propagation properties along receiver lines and source lines: the symmetric sampling provides an ideal data set for this approach.

The obtained velocity volume shows extreme variations, with sharp boundaries, steeply dipping layers, and velocity inversions. The presence of velocity inversions (low-velocity layers below faster formations) is confirmed by the lithological logs of some of the upholes available in the area.

The velocity volume contains spatially consistent features: a velocity slice at the elevation of 100 m asl is shown in Figure 2. This slice is at a depth of 50 to 100 m below the surface.

The Rayleigh wave inversion provided a shear-wave velocity volume, which must be converted into P-wave velocity for further processing. The conversion is performed using uphole data available from two previous campaigns. A total number of 21 upholes were considered. First, the lithology logs were analysed and compared to the velocity structure. Second, the uphole data and velocity information are QC'd; some upholes are rejected due to acquisition issues and unreliable velocity information.

Finally, the selected uphole P-wave velocities are cross plotted versus the inverted velocities to evaluate the correlation and calibrate a power conversion law. The large range of shallow velocities, from 300 m/s to 1300 m/s, and the absence of a shallow water table, results in a good correlation between both.

Results

An integrated near-surface velocity model is generated based on the surface-wave inversion, converted using refraction and uphole data: the resulting model is used to compute the near-surface perturbation corrections.

In time imaging, the velocity model is used to compute statics corrections. The static model is derived for sources and receivers: the final map of the receiver and source statics is shown in Figure 3.

Perturbations induced by the large lateral velocity variations in the near surface are large, and simple elevation statics fail at generating a coherent stack in the shallow section. The model-based statics provide a clear improvement with respect to elevation statics: the continuity of shallow events is improved, the coherency of the section and the stack response are improved, and some of the shallow events assume a simpler shape.

In Figure 4, the comparison between the stack with elevation statics and with the model-based statics is shown for one of the target lines, together with the corresponding near-surface velocity sections.

Conclusions

The application of an integrated near-surface characterization, based on surface-wave inversion, provided a high-resolution near-surface model for very complex geology in a thrust belt area. Despite the data complexity and the high level of incoherent noise, the surface-wave analysis extracts stable dispersion data from the dense point-receiver data set. The surface-wave
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Inversion model revealed an extremely challenging velocity structure in the shallow near surface, with sharp and large velocity variations due to lithological boundaries, steeply dipping layers, and velocity inversions. The calibration using upholes and the validation with local near-offset refractions produced a velocity model that provided an effective static solution and an initial shallow velocity model.

The near-surface model has also an intrinsic exploration value: it delineates with high-resolution the structural elements that have expressions in the near surface, and in some cases, can be used for geological modeling.

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Figure 1: Data with aliased and scattered surface waves, standard f-k spectrum, and supergather spectrum.

Figure 4: Example of a shallow stack section. Top: with elevation statics, bottom: with model-based statics. The shallow velocity model is shown in the middle panel.
EDITED REFERENCES
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