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Near-surface fault detection by migrating back-scattered surface waves with and without velocity profiles

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ABSTRACT

We demonstrate that diffraction stack migration can be used to discover the distribution of near-surface faults. The methodology is based on the assumption that near-surface faults generate detectable back-scattered surface waves from impinging surface waves. We first isolate the back-scattered surface waves by muting or FK filtering, and then migrate them by diffraction migration using the surface wave velocity as the migration velocity. Instead of summing events along trial quasi-hyperbolas, surface wave migration sums events along trial quasi-linear trajectories that correspond to the moveout of back-scattered surface waves. We have also proposed a natural migration method that utilizes the intrinsic traveltime property of the direct and the back-scattered waves at faults. For the synthetic data sets and the land data collected in Aqaba, where surface wave velocity has unexpected perturbations, we migrate the back-scattered surface waves with both predicted velocity profiles and natural Green's function without velocity information. Because the latter approach avoids the need for an accurate velocity model in event summation, both the prestack and stacked migration images show competitive quality. Results with both synthetic data and field records validate the feasibility of this method. We believe applying this method to global or passive seismic data can open new opportunities in unveiling tectonic features.

1. Introduction

Surveys in engineering and exploration are used to detect the distribution of near-surface faults. Accurate fault maps can be used to avoid unsafe construction of buildings or placement of drilling platforms. Detecting hidden faults near the surface can also be used to predict the optimal location of paleo seismic trench surveys that determine the magnitude and recurrence intervals of ancient earthquakes.

Shallow seismic surveys indirectly detect the presence of near surface faults by computing reflection sections, and inferring faults from the discontinuities of the reflection horizons. This indirect procedure is often successful, but it requires careful processing of the data to extract the reflection events, estimation of the correct stacking velocity, and sometimes a rigorous estimate of the statics. Moreover, the very early arrivals are muted due to the limitations in source-receiver sampling, so the reflectors very close to the surface are ignored. Such ignorance might prevent the detection of faults within several wavelengths of the free surface. For interferometric processing of passive seismic data, body-wave reflections are very difficult to extract, especially from shallow layers.

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This paper proposes the direct detection of near-surface faults by diffraction migration and natural migration of back-scattered surface waves. The faults are directly detected by migrating the back-scattered surface waves to their place of origin along the fault. The key assumption is that near-surface faults generate detectable back-scattered surface waves from impinging surface waves. This migration procedure is related to the interferometry method proposed by Schuster et al. (2012) except that the data are directly migrated, rather than interferometrically redatumed, for trial image points on the surface. The processing steps are to isolate the back-scattered surface wave events (Yu et al., 2014), and then to migrate them by diffraction migration using the surface wave velocity as the migration velocity. Instead of summing events along trial hyperbolas, surface wave migration sums events along trial quasi-linear trajectories that correspond to that of the backscattered surface waves. A deconvolution filter is also derived from the data, and it can collapse the dispersed surface wave arrival into a non-dispersive event whenever necessary. In this study, the velocity distribution is either a constant, or an estimated one by velocity scan, or not necessarily required for migration due to a proposed natural migration method by extracting Green's function from the data. Results with synthetic data and field records validate the feasibility of this method.

This paper is organized into four sections. The first part is the introduction, and the second part presents the theory. The third part shows numerical results with both synthetic data and field data. The field data are for a seismic survey over a desert region in Aqaba (Thuwal, Saudi Arabia) with faults at the near surface. The final section presents the conclusions.

2. Theory of surface wave migration

2.1. Migration of back-scattered surface waves

The vertical-component particle velocity of a propagating Rayleigh wave over a homogeneous half space can be approximated by the Green's function:

$$G(\mathrm{g}|\mathrm{s}) = W(\omega)A(\mathrm{g},\mathrm{s})e^{ik|\mathrm{g}-\mathrm{s}|}e^{-\kappa|z|}, \tag{1}$$

where the source at **s** and vertical-component particle-velocity geophone at **g** are both on the free surface (Aki and Richards, 1980), z is the depth, and κ is the vertical component of the wavenumber vector. The horizontal wavenumber is given by $k=\omega/c$, where c represents the Rayleigh wave velocity in a homogeneous medium (like one block in Fig. 1(a)) and ω is the angular frequency of the vertical component point source on the free surface. The term $A(\mathbf{g},\mathbf{s})$ takes into account the geometrical spreading of the surface wave from **s** to **g** and $W(\omega)$ is the source wavelet spectrum with the frequency ω that also includes a phase term associated with the Green's function for the surface wave; for convenience we will assume that this phase term is deconvolved from the data. The errors that the approximation makes largely attribute to the neglects of the radiation pattern and the body wave's contribution to the Green's function (Snieder, 1986). As an example, Fig. 1(b) shows the simulated surface waves for a model with three homogeneous blocks of velocity. The back-scattered surface waves (Fig. 1(c)) are the events that moveout in the opposite direction of the incident surface wave. These records are computed by a finite-difference solution to the 2D elastic wave equation (Virieux, 1986).

Previous work (Snieder, 1986; Blonk and Herman, 1994; Campman et al., 2003; van Wijk, 2002; Luke and Calderón-Macías, 2008) on imaging Rayleigh wave scattering from impedance discontinuities approximates the scattered waves at the free surface as a weighted surface integral of Green's tensors that take into account surface-wave propagation. The weights are impedance discontinuities s(**x**) on the free surface or very near the free surface and the integration is over the free surface; the impedance discontinuity can be considered to be a function of frequency to account for depth variations in the impedance function. The inverse to this integral equation gives the impedance distribution. In our proposal, we simply assume that the surface-wave response to an impedance discontinuity represented by a near-surface fault can be approximated by a surface integral of Green's functions weighted by the impedance discontinuity associated with the fault. Instead of inverting this equation in the least squares sense, we will simply apply its adjoint to the data to get the migration image on the surface.

The following steps are to migrate the back-scattered surface waves to their origin point along the fault near the surface. The important assumption is that the dominant back-scattered arrivals are from the near-surface portions of the fault. This assumption is reasonable and can be partly illustrated by a field data set in the next section.

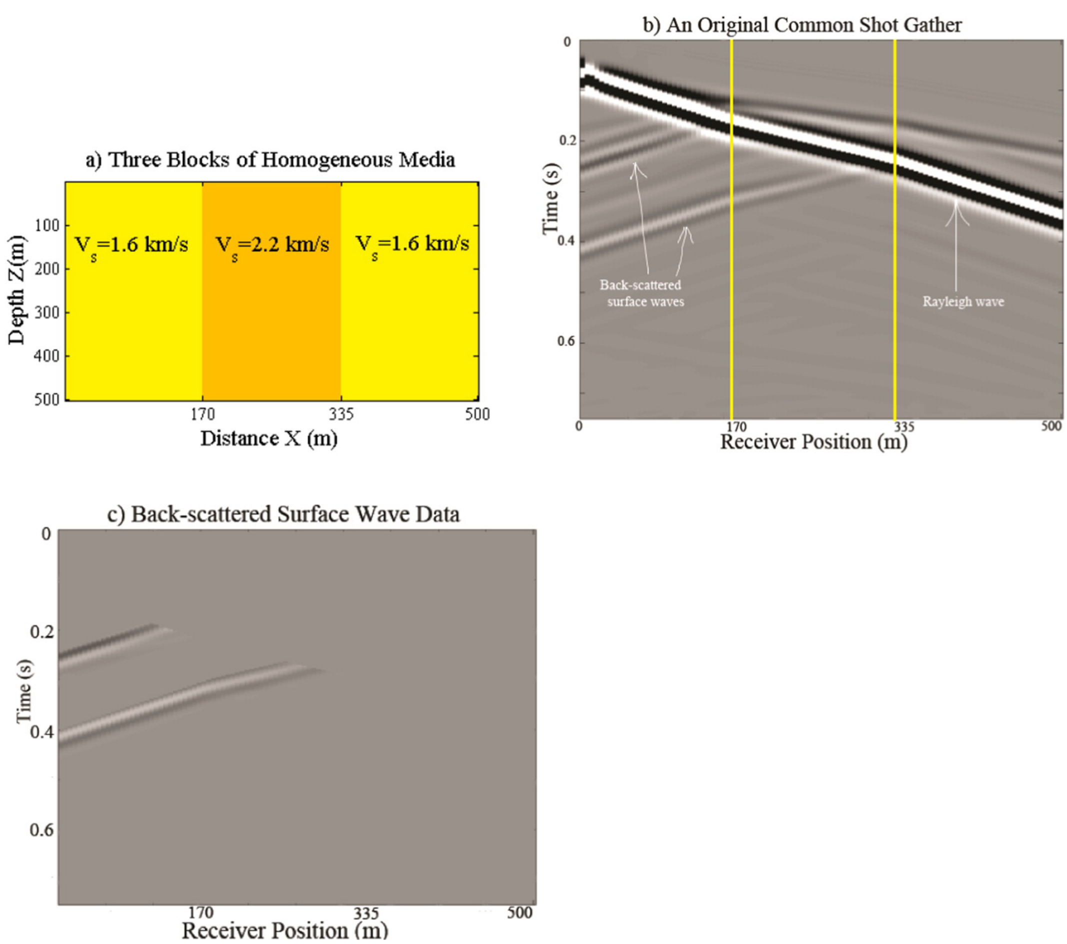

Fig. 1. a) Three blocks of homogeneous media to generate surface waves, b) surface wave records for a vertical displacement point source at ($x_s = 5$ m, $z_s = 0$ m) and vertical component geophones on the free surface, c) the back-scattered surface waves after muting. The two vertical lines in Fig. 1(a) are the faults that separate one velocity block from another. The two yellow vertical lines in Fig. 1(b) mark the position of the two faults. The velocities determine those of the simulated Rayleigh waves. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)