Estimation of pseudo-2D shear-velocity section by inversion of high frequency surface waves

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Summary

A scheme to generate pseudo-2D shear-velocity sections with high horizontal resolution and low field cost by inversion of high frequency surface waves is presented. It contains six steps. The key step is the joint method of crossed correlation and phase shift scanning. This joint method chooses only two traces to generate image of dispersion curve. For Rayleigh-wave dispersion is most important for estimation of near-surface shear-wave velocity, it can effectively obtain reliable images of dispersion curves with a couple of traces. The result of a synthetic example shows the feasibility of this scheme.

Introduction

The shear-wave velocity of near-surface materials (soil, rocks, and pavement) and its effect on seismic-wave propagation are of fundamental interest in many groundwater, engineering, and environmental studies (Xia et al., 1999). Because the S-wave velocity is the dominant property of the fundamental mode of Rayleigh wave dispersion data, S-wave velocities can be quickly estimated from surface wave data (Xia et al., 1999; Park et al., 1999). Pseudo-2D shear-velocity sections are constructed by aligning 1D models at each spread midpoint.

As we all known, extracting the shear-wave velocity profile from Rayleigh-wave measurements is less straightforward and this usually entails a two step process in which the dispersion curves of Rayleigh are firstly calculated. During many dispersion curve imaging methods, the phase shift method developed by Park et al. (1998) has been proved as better overall resolution (Beaty et al., 2003). However, this method needs multi-channel record to generate images of dispersion curves. More traces taken for calculation, better image of dispersion curves can be obtained if proper field acquisition parameters are chosen. As mentioned before, the inverted shear velocity is an average over each spread, so the number of the traces used to image dispersion curves directly determines the horizontal resolution of surface wave surveys. Xia et al. (2005) applied a generalized inversion to pseudo-2D sections in the horizontal direction to remove the inconsistencies and provide an improvement in horizontal resolution. But this method needs redundant work in the same survey point.

An appealing alternative solution to generate pseudo-2D sections can be obtained by inversion of dispersion curves calculated through a crossed correlation method (Guo et al., 1999; Liu et al., 2003). A crossed correlation method just chooses a pair of any two receivers in one line to calculate dispersion curves. This method can greatly improve the horizontal resolution of pseudo-2D sections without the demand of acquiring redundant field data. But this method is sensitive to data processing and the unrealistic results will be generated if the data has very low signal-to-noise ratio.

We present a scheme to generate pseudo-2D shear-velocity sections with high horizontal resolution and low field cost. In this scheme, a pair of traces is chosen to image the dispersion curve using crossed correlation method with phase shift scanning. The purpose of this method is to obtain high creditable dispersion curves with high horizontal resolution for inversion. To demonstrate the feasibility of this scheme, a synthetic example is used for estimation of pseudo-2D section.

The method

We first introduce the method of crossed correlation with phase shift scanning. We then present the scheme to illustrate the processing flow of obtaining pseudo-2D shear-velocity sections.

Crossed correlation with phase shift scanning

Considering offset-time (x-t) domain representation $u_1(t)$ and $u_2(t)$ of two traces of surface wave record, $U_1(f)$ and $U_2(f)$ can be obtained by Fourier transformation. The auto power spectra for these two records are expressed as:

$$P_{11}(f) = U_1(f) \cdot U_1^*(f) \tag{1}$$

$$P_{22}(f) = U_2(f) \cdot U_2^*(f) \tag{2}$$

where $U_1^*(f)$ and $U_2^*(f)$ are the complex conjugate of $U_1(f)$ and $U_2(f)$. The cross power spectrum between these two records is:

$$\begin{aligned} P_{21}(f) &= U_2(f) \cdot U_1^*(f) \\ &= \left|U_2(f)\right| \cdot \left|U_1^*(f)\right| e^{i\Delta\phi(f)} \end{aligned} \tag{3}$$

where $\Delta\phi(f)$ is the phase shift in a given frequency f. Guo et al. (1999) use the correlation function $C(f)$ To quantify the correlation as:

$$C(f) = \frac{P_{21}(f) \cdot P_{21}^*(f)}{P_{11}(f) \cdot P_{22}(f)} \tag{4}$$

Guo et al. (1999) pointed out that if the system is linear, the absolute value of $C(f)$ is close to unity and it is usually select $C(f)=0.8\sim 1$ to define the phase shift. The formula to calculate the phase velocity is:

$$v_R(f) = \frac{2\pi f \Delta x}{\Delta\phi} \quad (5)$$

Where $v_R(f)$ is the phase velocity of Rayleigh wave and Δx is the distance between two traces.

The crossed correlation method described above can image dispersion curve of any two traces. But the reliability of the dispersion curve is low and unrealistic points in dispersion curves will greatly distort inversion. Here we join crossed correlation method with phase shift scanning to image dispersion curves. The phase shift scanning method is something like the slant stack. We can see that the correlation value $C(f)$ is the function of phase shift $\Delta\phi$ at a given frequency f. So a series values can be obtained by scanning $\Delta\phi(f)$. For a value of $\Delta\phi$ at a given frequency f where a peak of $C(f)$ occurs, the phase velocity $v_R(f)$ can be determined by formula (5). By joining phase shift scanning to crossed correlation method, image of dispersion curve can be achieved instead of only dispersion curve obtained by crossed correlation method.

The scheme

The processing flow of obtaining pseudo-2D shear-velocity sections is as follows:

1. Applying Fourier transformation to obtain the signal amplitudes and angles of two traces.

2. Calculating the auto and cross power spectrum.

3. Phase shift scanning to get the image of dispersion curve.

4. Using a trial-and-error method to extract the dispersion curve from the image.

5. Estimation of shear velocities by L-M method with SVD technique developed by Xia et al. (1999).

6. Generation of a pseudo 2D shear-velocity section.

Steps 1 to 5 are repeated to generate a number of shear velocity profiles. Figure 1 show these steps. Two traces in figure 1(a) are used for the estimation of shear velocities. Image of dispersion curve is presented in figure 1(b). Rayleigh-wave phase velocity is then extracted from the image in the f-v domain (figure 1(c)). Finally, the phase velocity is inverted for a shear velocity profile (figure 1(d)).

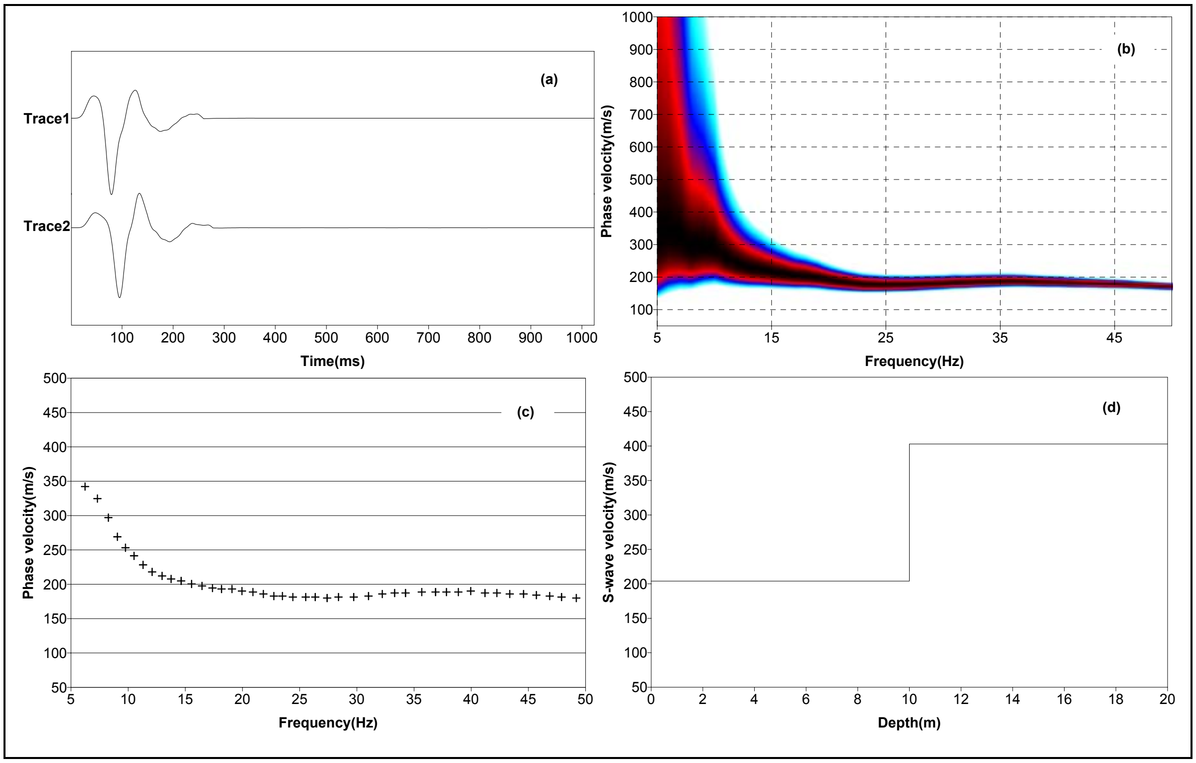

Figure 1: A diagram of inverting 1D shear-velocity profile. (a) two traces; (b) the image of dispersion curve; (c)Rayleigh-wave phase velocity in the f-v domain; and (d) the shear velocity profile.

A synthetic example

High frequency surface waves (figure 2) due to a 2D model (figure 3) were simulated using a finite difference method (Xu et al., 2005). In this model, a corner edge was designed to simulate a vertical fault in a near-surface. In the finite difference method, spatial grid size was 1 meter with time step of 0.1 ms; source is described by the first-order derivative of Gaussian function $t \cdot \exp(-at^2)$ with controlling parameter $a = 3000$; the nearest shot-geophone offset was selected as 6 meters with 1 meter geophone interval. 50-channel records were simulated and the vertical fault was in the middle of the spread. The shot gather (vertical component) are shown in figure 2.

As 50 traces, 49 couples were extracted for calculating the images of dispersion curves. Each couple consists of two traces with 1 meter distance. So 49 images were generated and the corresponding dispersion curves for inversion were extracted (For page limitation, the figures were not shown in this paper). Then the fifth step of the scheme is taken to estimate of shear velocity profiles. Forty-nine profiles inverted by 1D model-based inversion and were recorded as the average of every two traces. So the pseudo-2D shear-velocity sections were constructed by aligning these 1D profiles. The pseudo-2D sections can reveal the lateral changes of shear velocity.

Figure 3 shows the pseudo-2D shear-velocity section. It clearly shows that a corner edge in the place of 25 meters in distance axis can be determined. We can easily interpret this section as: the former part of the section (distance smaller than 25 meters) consists of two layers and the thickness of the upper layer is 10 meters; the middle part (25 meters at the distance axis) is almost a vertical fault and the upper and the lower breaking points are at 5 and 10 meters; and the last part is also a 1D structure consisting of two layers and the thickness of the upper layer is 5 meters. The section fits with the model very well. The synthetic example demonstrates that the scheme described above is feasible.

Conclusions

As a fast, inexpensive, and non-destructive method, high-frequency surface wave has been widely used to estimate of near-surface shear-wave velocity. We present a scheme to generate high resolution pseudo-2D shear-velocity sections with low field costs. In this scheme, a pair of traces is chosen to image the dispersions using crossed correlation method with phase shift scanning. So we can obtain a 1D shear-velocity profile with only two traces. By aligning these 1D profiles, the scheme greatly improves the horizontal resolution of pseudo 2D sections without adding redundant field work. The synthetic example demonstrates the feasibility of this scheme.

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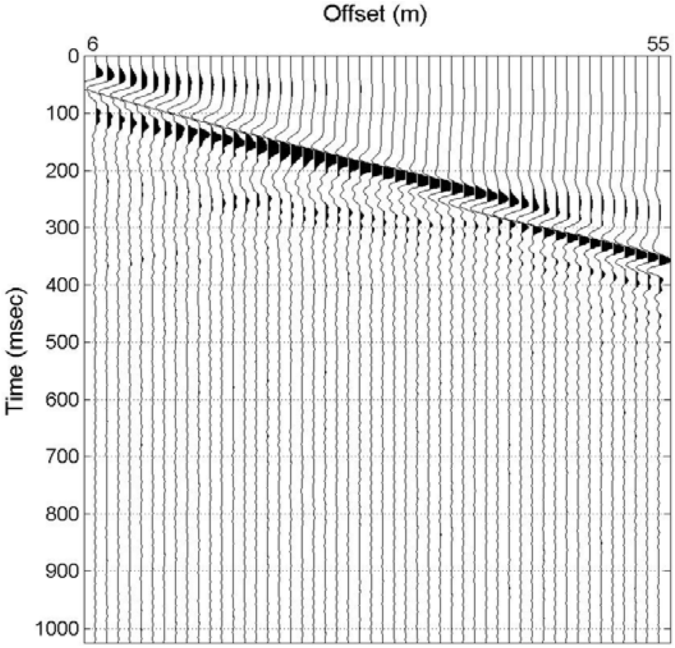

Figure 2: The vertical particle velocity

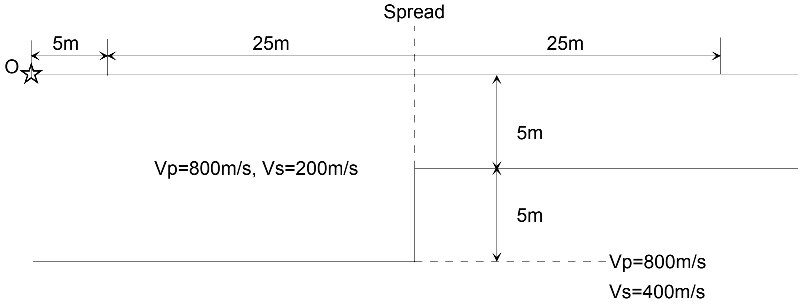

Figure 3: Illustration of a corner-edge model and layouts of sources and receivers

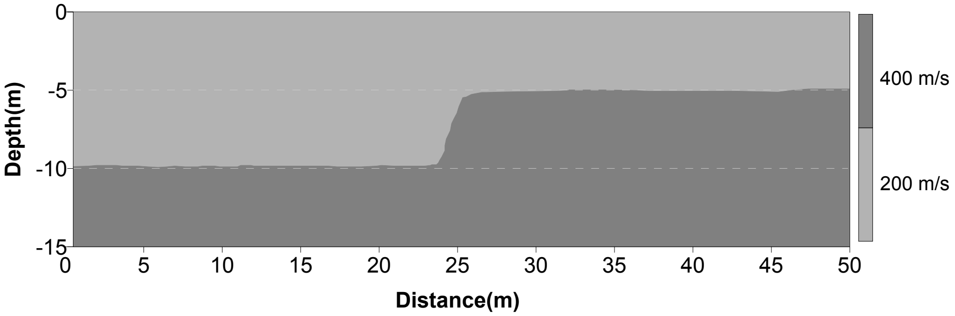

Figure 4: The pseudo-2D shear-velocity section of the corner-edge model

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