Effect of Lateral Heterogeneity in the Soil Column on Shear-Wave Velocity Estimation by Rayleigh-Wave Inversion

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Summary

We conducted elastic wavefield modeling of shot gathers using soil-column models with vertical and lateral velocity variations to study the dispersive behavior of Rayleigh waves and the effect of lateral heterogeneity on the accuracy of Rayleigh-wave inversion for shear-wave velocity estimation. We also conducted a field experiment over an alluvial valley with soil column that thins out in the direction orthogonal to the valley axis. From the model and field experiments, we found that the dispersion characteristics of Rayleigh waves is greatly influenced by the geometry of and lateral heterogeneities within the soil column. Nevertheless, estimation of shear-wave velocities within a soil column with lateral heterogeneity by Rayleigh-wave inversion is sufficiently robust and accurate for geotechnical applications.

Model Experiments

We built a set of 2-D soil-column velocity-depth models with horizontal and dipping layers, models with faults and arbitrary layer geometries, and models with perturbed layer velocities. An example for model parameters is listed in Table 1. By performig elastic wavefield modeling (Larsen and Schultz, 1995), we then generated shot gathers using the recording parameters listed in Table 2. An example of 2-D elastic wavefield modeling of shot gathers is shown in Figure 1. Although the soil column behaves most likely as a viscoelastic medium insofar as seismic wave propagation and there can be differences in elastic and viscoelastic Rayleigh-wave dispersion (Zhang et al., 2010), we decided to perform elastic wavefield modeling so as to utilize the Rayleigh-wave inversion for shear-wave velocity estimation based on elastic wave theory (Xia et al., 1999).

Table 1. Model 4a parameters for the soil column.

Depth	*Vp*	*Vs*	*Vp/Vs*	*Density*
0	500	100	5	1.8
5	600	150	4	1.8
10	700	200	3.5	1.8
15	875	250	3.5	2
20	1050	300	3.5	2
25	1225	350	3.5	2
30	2450	700	3.5	2.4

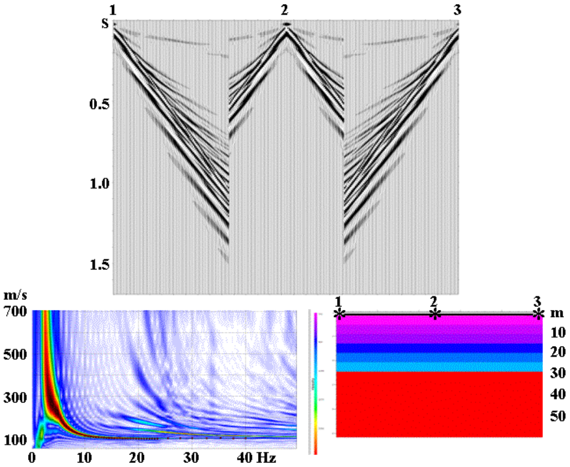


Figure 1. Top: Three shot gathers generated by 2-D elastic wavefield modeling associated with the soil column Model 4a with parameters listed in Table 1. Shown at the bottom are the dispersion spectrum (left) calculated from shot record 1 that exhibits the Rayleigh-wave modes, and the P-wave velocity-depth model of the soil column (right).

Table 2. Recording parameters for 2-D elastic modeling of shot gathers

Number of shots	3
Number of traces per shot	96
x-coordinate of the first shot	448 m
x-coordinate of the second shot	497.5 m
x-coordinate of the third shot	547 m
Recording geometry	same receiver spread for all three shots
x-coordinate of the first receiver	450 m
Receiver interval	1 m
Shot depth	0 m
Source wavelet bandwidth	2-64 Hz min-phase Ricker with 13-Hz dominant frequency
Sampling rate	1 ms
Recording length	2 s

From the first set of model experiments (Figure 2) we observe that (a) within a single-layered soil column (Models 1a,b,d) with increasing thickness from 5 to 30 m, Rayleigh waves become increasingly less dispersive; (b) for the same soil-column thickness of 30 m, Rayleigh waves become more dispersive when we introduce vertical velocity variation (Models 1d,i); and (c) the dispersive character of Rayleigh waves becomes more prominent when we introduce layers within the soil column (Models 1d,i and Model 4a).

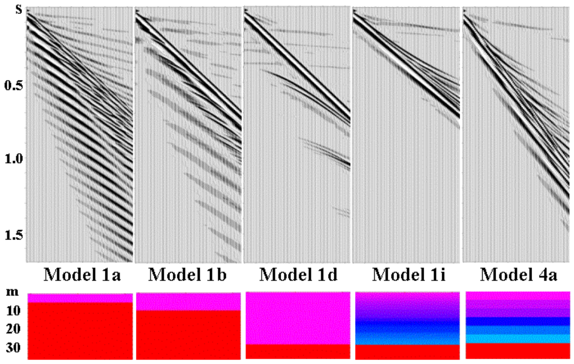


Figure 2. Shot gathers generated by 2-D elastic wavefield modeling associated with the soil column Models 1a,b,d,i and Model 4a. Shown at the bottom are the the P-wave velocity-depth models of the soil column.

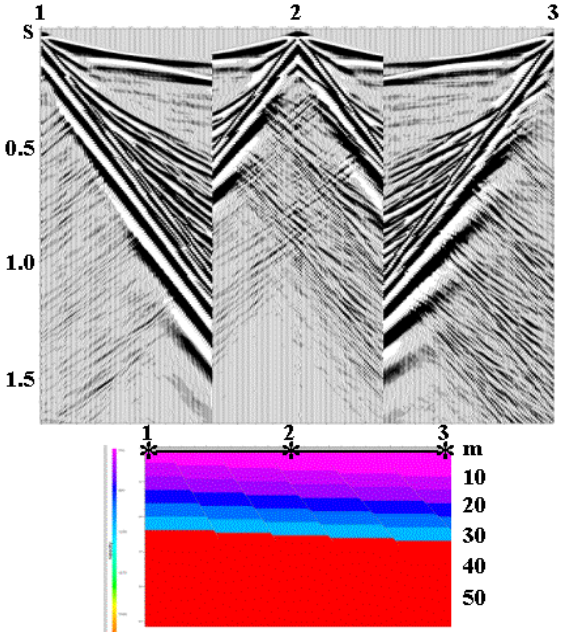
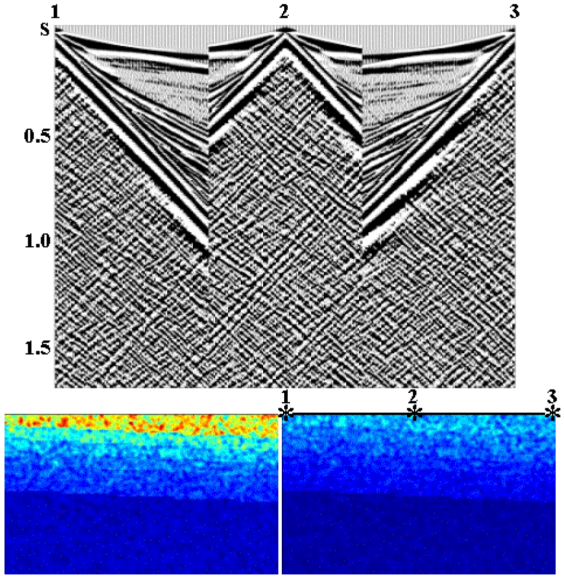


Figure 3a. Shot gathers generated by 2-D elastic wavefield modeling associated with the soil column Model 4a with model parameters listed in Table 1, but modified by inclusion of en-echelon faults as shown at the bottom. Note the back-propagated Rayleigh waves from the fault discontinuities and the aysmmetry of shot records 1 and 3 caused by lateral velocity variations.

From the second set of model experiments, with two examples shown in Figures 3a,b, we observe that (a) Rayleigh waves are back-propagated at discontinuities within the soil column with lateral velocity variations (Figure 3a), and (b) backscattered when there is a short-wavelength heterogenetiy within the soil column (Figure 3b).



perturbed S **perturbed P**

Figure 3b. Shot gathers generated by 2-D elastic wavefield modeling associated with the soil column Model 4a with model parameters listed in Table 1, but modified by inclusion of en-echelon faults as in Figure 3a and perturbation of P- and S-wave velocities as shown at the bottom. Note the superposition of back-propagated Rayleigh waves caused by fault discontinuities and backscaterring caused by velocity perturbations.

Veloicty Analysis

Shallow seismic data have long been used to estimate P- and S-wave velocities for the soil column for geotechnical applications (Yilmaz et al., 2006a,b). By applying a nonlinear traveltime tomography (Zhang and Toksoz, 1998) to the first-arrival times picked from the three shot records for each soil column model, we estimated a P-wave velocity-depth model along the receiver spread useed to create the shot records (Table 2). By applying smoothing during the inversion and lateral averaging after the inversion, we then obtained a P-wave velocity-depth profile representative of each soil column model (Figure 4). Next, we applied plane-wave decomposition to transform the off-end records for each soil column model from offset-time to phase-velocity versus frequency domain. A dispersion curve associated with the fundamental mode of Rayleigh-type surface waves was picked in the transform domain based on the maximum-energy criterion and inverted to estimate the S-wave velocity as a function of depth as shown in Figure 4 (Park et al., 1999; Xia et al., 1999). Results of the velocity analysis shown in Figure 4 and the results from all of the soil column models not shown here indicate that estimation of shear-wave velocities within a soil column with lateral heterogeneity by Rayleigh-wave inversion is sufficiently robust and acceptable within the bounds of the accuracy required for geotechnical applications.

Field Experiments

We conducted a field experiment in an alluvial valley using a buffalo gun and a receiver spread with 48 4.5-Hz vertical geophones at 2-m interval. We acquired two off-end shot records along the receiver spread parallel to the valley axis (BG1 and BG2 in Figure 5) and two off-end shot records along the receiver spread orthogonal to the valley axis (BG1 and BG2 in Figure 5). Note that the dispersive pattern of Rayleigh waves exhibits variations in the two records along the same spread shot in opposite directions. Also, the dispersive pattern of Rayleigh waves exhibits variations along the two receiver spreads orthogonal to each other. All four records shown in Figure 5 indicate that shear-wave velocities must vary in the lateral direction within the alluvial valley soil column.
We picked the fundamental modes from the dispersion spectra computed from the shot records in Figure 5 and performed Rayleigh-wave inversion to estimate the shear-wave velocity-depth profiles in the two orthogonal directions (Figure 6). The two velocity-depth profiles exhibit some differences which we should attribute, not to anisotropy, but, based on the model experiments, to the differences in the geometry of the valley profile along the two orthogonal directions.

Conclusions

Elastic wavefield modeling and a field experiment over an alluvial valley with soil column that thins out in the direction orthogonal to the valley axis show that the dispersive behavior of Rayleigh waves is greatly influenced by the geometry of and lateral heterogeneities within the soil column. Specifically, within a single-layered soil column with decreasing thickness, Rayleigh waves become increasingly more dispersive; for the same soil-column thickness, Rayleigh waves become more dispersive when we introduce vertical velocity variation; and the dispersive character of Rayleigh waves becomes more prominent when we introduce layers within the soil column. Model experiments further show that Rayleigh waves are back-propagated at discontinuities within the soil column with lateral velocity variations, and backscattered when there is a short-wavelength heterogenetiy within the soil column.

Results from the field experiments suggest that estimation of shear-wave velocities within a soil column with lateral heterogeneity by Rayleigh-wave inversion is sufficiently robust and accurate for geotechnical applications.

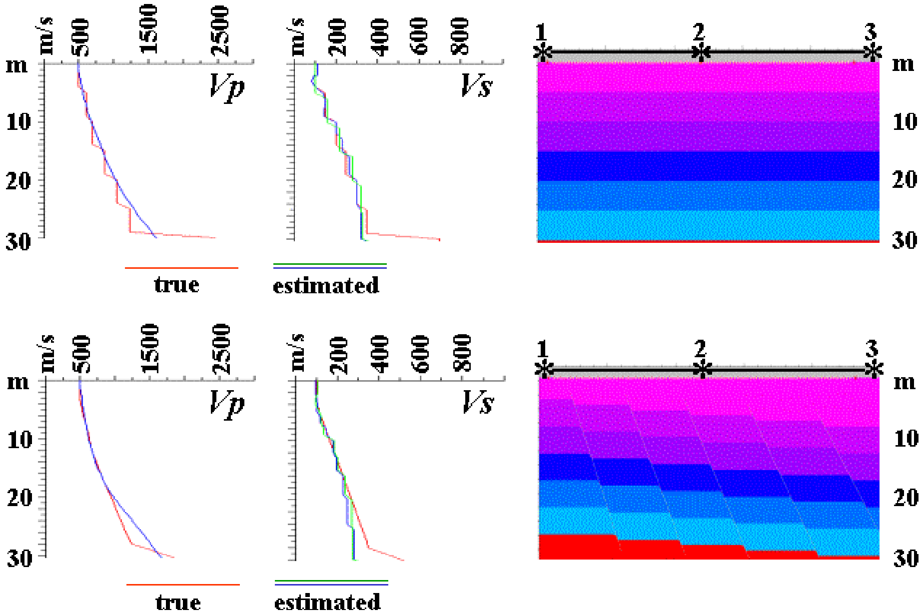


Figure 4. Velocity estimation from the shot records for the soil column Model 4a (top) and the same model modified with en-echelon faults (bottom).

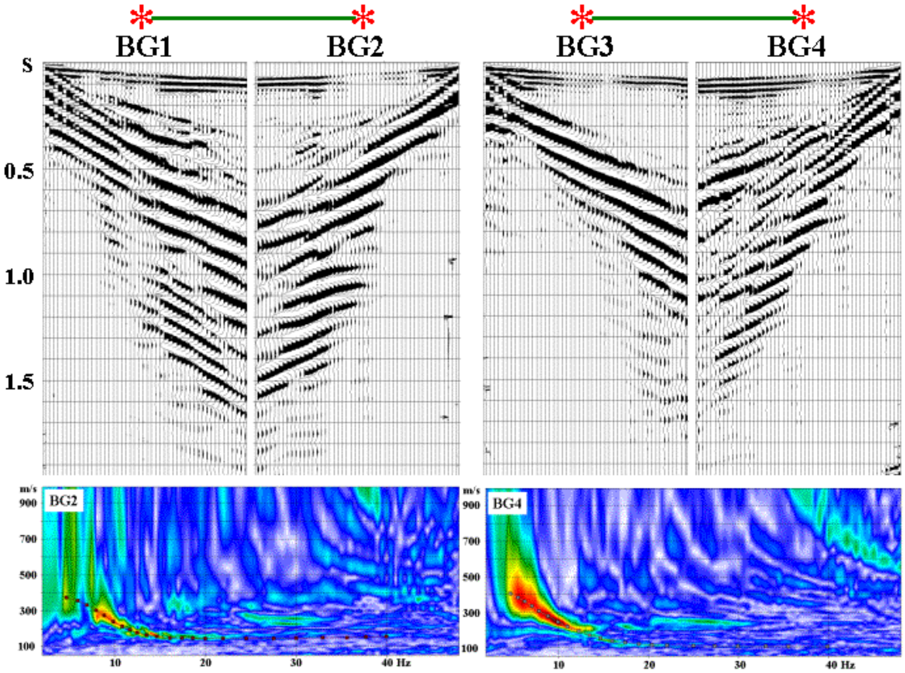


Figure 5. Field records from an experiment in an alluvial valley using a buffalo gun and a receiver spread with 48 4.5-Hz vertical geophones at 2-m interval. BG1 and BG2: off-end shot records along the receiver spread (the green bar) parallel to the valley axis and BG3 and BG4: off-end shot records along the receiver spread orthogonal to the valley axis. Bottom: the dispersion spectra computed from shots BG2 and BG4.

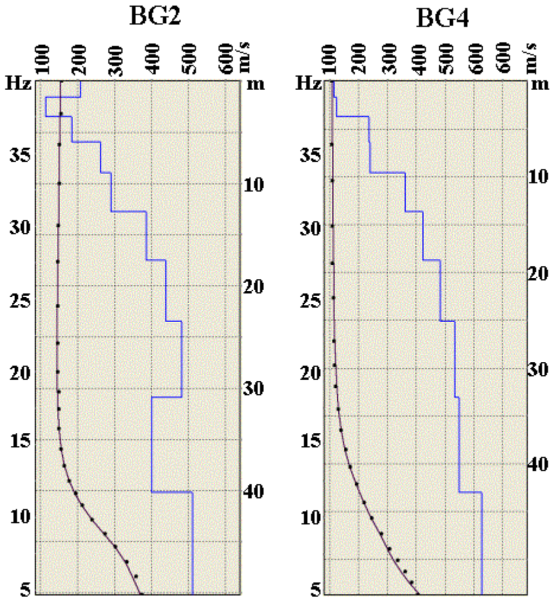


Figure 6. Shear-wave velocity-depth profiles estimated from a field experiment in an alluvial valley in two orthogonal directions. Field records and the dispersion spectra are shown in Figure 5. The black dots represent the dispersion curves for the fundamental mode picked from the dispersion spectra shown in Figure 5 and the black cvurves represent the modeled dispersion curves from Rayleigh-wave inversion.

EDITED REFERENCES

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