A Unified Workflow for Engineering Seismology

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Summary

We present a workflow for analysis of shallow seismic data to estimate a near-surface model defined by layer geometries within the soil column, and the P- and S-wave velocities of the layers themselves. Specifically, we use reflected waves in recorded shallow seismic data to derive a seismic image represented by a CMP stack and refracted waves to estimate a P-wave velocity-depth model of the near-surface. We then use the P-wave velocity field to perform time-to-depth conversion of the CMP stack so as to delineate the layer geometries within the soil column in depth. Additionally, we use Rayleigh-type surface waves to esimate an S-wave velocity profile in depth. We demonstrate the unified workflow for shallow seismic data acquired for coal and groundwater exploration, and geotechnical site investigations.

Introduction

The seismic method has three applications with different requirements for band-width and depth-width:

(1) Earthquake seismology with a bandwidth up to 10 Hz and a depth of interest down to 100 km,
(2) Exploration seismology with a bandwidth up to 100 Hz and a depth of interest down to 10 km, and
(3) Engineering seismology with a bandwidth up to 1000 Hz and a depth of interest down to 1 km.

Each of the three categories of seismology makes use of a specific wave type:

(1) In earthquake seismology, dispersion of surface waves is used to delineate velocity-depth models for the oceanic and continental crusts.
(2) In exploration seismology, reflected and diffracted waves are used to derive an image of the subsurface.
(3) In engineering seismology, refracted waves are used to derive a velocity-depth model for the near-surface.

For a specific category of seismology, the associated wave type is considered signal, while other wave types are considered noise. For instance, surface waves are essential for earthquake seismology, while they are treated as coherent linear noise in exploration seismology --- ground roll in land seismic exploration and guided waves in marine seismic exploration.

In the unified workflow for engineering seismology presented here, we make use of all three wave types:

(1) Apply a simple conventional processing sequence to obtain a CMP stack associated with the reflected waves.
(2) Perform inversion of traveltimes associated with the refracted waves to estimate a near-surface P-wave velocity-depth model and use it for time-to-depth conversion of the CMP stack section. Then, interpret this section in depth to delineate the geometry of the layers within the soil column and the geometry of the soil-bedrock interface.
(3) Perform inversion of the Rayleigh waves to derive an S-wave velocity profile in depth.

The workflow for analysis of shallow seismic data described above provides a near-surface model defined by layer geometries within the soil column, and the P- and S-wave velocities of the layers themselves. The layer thicknesses and S-wave velocities within the soil column yield the characteristic site period --- an important geotechnical parameter for soil remediation and building design. The near-surface model also can be used to compute an accurate response spectrum and thus estimate the amplification factor for the soil column. Additionally, the P- and S-wave velocities associated with the near-surface can be used to compute a Poisson's ratio profile in depth. Finally, assuming an empirical relation between density and P-wave velocities, modulus of rigidity profile in depth can be computed. The Poisson's ratio relates to fluid saturation and modulus of rigidity describes stiffness of the layers within the soil column.

Application to Field Data

We have applied the unified workflow for engineering seismology to coal and groundwater exploration, and geotechnical site investigations. Here we shall present an example that demonstrates the entire workflow.

The shallow seismic data were acquired using a 48-channel seismic recording system with 10-Hz geophones and an explosive source that uses a pipe-gun with a 50-gram shell placed in a 30-cm hole. Both the receiver and shot station intervals are 2-m. The data acquisition parameters are listed in Table 1. The receiver stations (101-148) are kept the same for all shots, while the shots themselves are moved starting from one end of the line to the other (89-163). This recording geometry yields a minimum fold of 12 at both ends of the line and a maximum fold of 48 at the center of the line. The CMP stack section that corresponds to the field geometry has a total length of 120 m with a 1-m CMP interval.

Table 1: Acquisition parameters.

Receiver interval	2 m
Number of receivers (channels) per shot	48
First and last receiver station	101-148
Shot interval	2 m
Number of shots	75
First and last shot point	89-163
Shot hole depth	30 cm
Charge size	50 gm
Min-max CMP fold	12-48
Sampling interval	0.5 ms
Trace length	1 s
Distance between first and last shot station	148 m
CMP interval	1 m
Number of CMPs (length of CMP stack)	120

Figure 1a shows a field record that exhibits a good reflection at 200 ms, excellent first breaks associated with the refracted arrivals, and a dispersive wave package associated with the Rayleigh-type surface waves.

Table 2 shows the workflow for reflection data analysis. The objective is to derive an image of the near-surface associated with the soil column and the underlying bedrock.

Table 2: Workflow for reflection data analysis.

1	Perform format conversion of the field records.
2	Merge recording geometry information with the seismic data.
3	Apply 48,60-240,300-Hz bandpass filter.
4	Apply 100-ms AGC.
5	Sort the shot data to CDP gathers.
6	Perform velocity analysis.
7	Apply NMO correction.
8	Stack the CDP gathers.
9	Apply 48-60-240,300-Hz bandpass filter.
10	Apply 40-ms AGC.

In contrast to a comprehensive processing sequence applied to reflection seismic data used in exploration for oil and gas fields (Yilmaz, 2001), shallow reflection seismic data usually require a simple processing sequence (Steeples and Miller, 1990) that includes application of a bandpass filter and AGC.

Figure 1b shows a CMP stacked section derived from the data recorded using the field parameters in Table 1 and analyzed using the workflow described in Table 2. The strong reflections at approximately 100 and 200 ms correspond to known coal seams in the area.

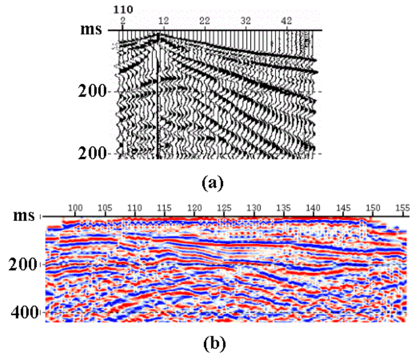


Figure 1. (a) A field record with a good reflection at 200 ms, and (b) the CMP stack derived from 75 shot records as in (a) using a simple processing sequence (Table 2).

Figure 2a shows a field record with first breaks picked for refraction inversion.

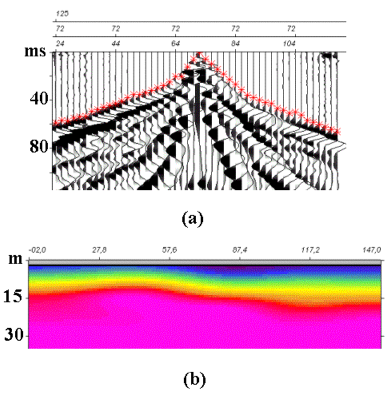


Figure 2. (a) A field record with picked first breaks, and (b) the P-wave velocity-depth model derived from refracted arrivals as in (a) using a traveltime inversion procedure (Table 3).

Table 3 shows the workflow for refraction data analysis. The objective is to estimate the P-wave velocities within the soil column and the underlying bedrock.

Figure 2b shows the P-wave velocity-depth model derived from refraction inversion (Zhang, J. and Toksoz, M. N., 1997) that is included in the workflow described in Table 3. Note that the near-surface image displayed in the CMP stack section in Figure 1b down to the first coal seam at 100 ms is consistent with the P-wave velocity-depth model shown in Figure 2b. This velocity field can be used to perform time-to-depth conversion of the CMP stack, which can then be interpreted to delineate the layer geometries within the soil column.

Table 3: Workflow for refraction data analysis.

1	Perform format conversion of the field records.
2	Merge recording geometry information with the seismic data.
3	Pick first breaks from shot records.
4	Construct an'initial' model for the near-surface that is defined by a set of horizontal layers each with a constant P-wave velocity.
5	Compute the refracted traveltimes associated with the initial model.
6	Perturb the initial model parameters until the difference between the modeled (step 5) and the observed (step 3) traveltimes is minimum in the least-squres sense, and create a 'final' model of the P-wave velocity field for the near-surface.

Figure 3a shows a field record with a dispersive wave package associated with Rayleigh waves. The near and far offsets are 24 m and 118 m, respectively.

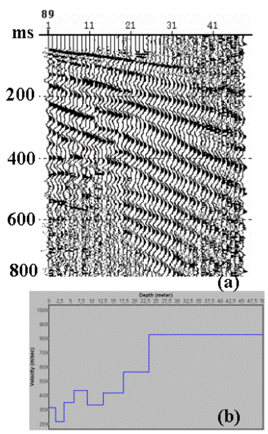


Figure 3. (a) A field record that exhibits a dispersive wave package associated with Rayleigh waves, and (b) the S-wave velocity profile in depth derived from the Rayleigh waves in (a) using an inversion procedure (Table 4).

Table 4 shows the workflow for Rayleigh-wave data analysis. The objective is to estimate the S-wave velocities within the soil column and the underlying bedrock.

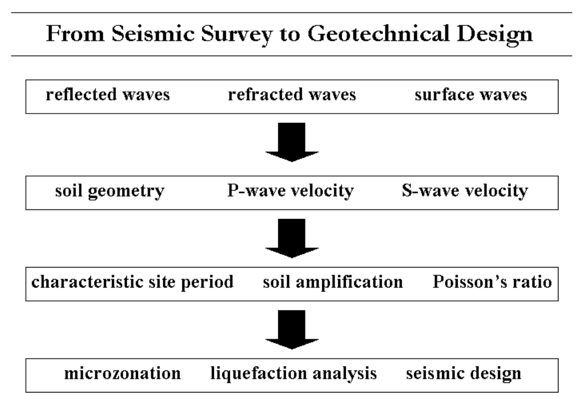
Figure 3b shows the estimated S-wave velocity profile as a function of depth for the near-surface from inversion of the fundamental mode associated with Rayleigh waves (Park et al., 1999; Xia et al., 1999) that is included in the workflow described in Table 4.

The layers within the soil column inferred from the S-wave velocity profile includes a low-velocity top soil with 2.5-m thickness, underlain by two layers with 400-m/s velocity down to a depth of 12.5 m, and with a velocity that gradually increases to about 800 m/s down to a depth of 22.5 m.

Table 4: Workflow for Rayleigh-wave data anlysis.

1	Perform format conversion of the field records.
2	Merge recording geometry information with the seismic data.
3	Mute the field record to exclude the zones outside the dispersed Rayleigh waves.
4	Apply 24,30-Hz high-cut filter.
5	Apply a 50-ms AGC.
6	Compute the dispersion curve that describes the phase velocity as a function of frequency.
7	Consider an 'initial model' for the P- and S-wave velocities, each, as a function of depth.
8	Compute the dispersion curve associated with the initial models for the P- and S-wave velocities.
9	Perturb the initial model parameters until the difference between the modeled (step 8) and the observed (step 6) dispersion curves is minimum in the least-squres sense, and create a 'final' model of the S-wave velocity profile for the near-surface.

The P- and S-wave velocities and layer geometries associated with the near-surface can be used to derive geotechnical parameters for the soil column (Figure 4).



Specifically, the layer thicknesses and S-wave velocities within the soil column are used to compute the characteristic site period. The response spectrum computed from the near-surface model is used to estimate the amplification factor for the soil column. The P- and S-wave velocities associated with the near-surface are used to compute a Poisson's ratio profile in depth. Finally, assuming an empirical relation between density and P-wave velocities, modulus of rigidity profile for the soil column is computed. Both Poisson's ratio and modulus of rigidity are important geotechnical parameters, which describe level of fluid saturation and stiffness of the layers within the soil column, respectively. The geotechnical investigations are further extended to include microzonation analysis, liquefaction analysis, and aseismic design of structures (Kaneko et al., 1990).

Conclusions

We presented a demonstrative example of a unified workflow for the analysis of engineering seismic data. The objective is to estimate a near-surface model defined by layer geometries within the soil column, and the P- and S-wave velocities of the layers themselves. We analyze reflected waves to derive a seismic image in the form of a CMP stack and refracted waves to estimate a P-wave velocity-depth model of the near-surface. We use the P-wave velocity field for time-to-depth conversion of the CMP stack, which then is interpreted to delineate the layer geometries within the soil column in depth. Additionally, we analyze Rayleigh waves to esimate an S-wave velocity profile in depth. The unified workflow for shallow seismic data presented here can be readily applied to coal and groundwater exploration, and geotechnical site investigations.

References

Kaneko, F., Kanemori, T., and Tonouchi, K., 1990, Low-frequency shear-wave logging in unconsolidated formations for geotechnical applications: *in* Geophysical applications in geotechnical investigations, Paillet, L. and Saunders, W., ed., Am. Soc. For Test. Matls., 79-98.

Park, C. B., Miller, R. D., and Xia, J., 1999, Multichannel analysis of surface waves: Geophysics, **64**, 800-808.

Steeples, D. W. and Miller, R. D., 1990, Seismic reflection methods applied to engineering, environmental, and groundwater problems: *in* Geotechnical and environmental geophysics, Ward, S. H., ed., Soc. of Expl. Geophys., Tulsa, OK, 1-30.

Xia, J., Miller, R. D., and Park, C. B., 1999, Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves: Geophysics, **64**, 691-700.

Yilmaz, O., 2001, Seismic data analysis --- processing, inversion, and interpretation of seismic data: Soc. of Expl. Geophys., Tulsa, OK.

Zhang, J. and Toksoz, M. N., 1997, Joint refraction traveltime migration and tomography: Proceedings of the Environmental and Engineering Geophysical Society, Reno, Nevada, 901-910.