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Model-Based Surface Wave Analysis and Attenuation

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Summary

Surface waves can significantly degrade overall data quality in seismic surveys. In this paper we present a method, which includes inversion and adaptive subtraction filtering of surface waves via a multi-scale technique, in order to attenuate or remove surface waves. The method utilizes a 1D viscoelastic layered model to generate synthetic surface waves through propagator matrix method. The inversion procedure estimates an optimal viscoelastic layered model through global and local optimization methods to minimize the misfit of dispersion spectra obtained from seismic and synthetic shot gathers. Since the 1D model obtained from the optimization methods cannot represent any lateral variations of physical parameters in earth, adaptive subtraction and multi-scale technique are applied to mitigate this limitation. The tests of a 3D field dataset indicate that the optimization methods can estimate an optimal model to generate the synthetic data suitable for adaptive subtraction. The tests also show that the method is robust and efficient for surface-wave attenuation.

Introduction

Surface waves, such as Rayleigh wave, travel at or near ground surface and are the result of interfering *P*- and *S*-waves. A low-velocity Rayleigh wave can generate coherent noise, usually known as ground roll, in seismic surveys. The coherent noise is typically characterized by low frequencies and high amplitudes. In practice the waves also exhibit dispersive character due to attenuation. Since ground roll can significantly degrade overall data quality, it must be attenuated or removed.

Based on the characteristics of ground roll, various techniques have been developed to eliminate this noise. Traditional filtering methods in f-k or τ-p domains can effectively attenuate ground roll (Carry and Zhang, 2009). However, the filtering methods can suffer from irregular trace spacing, data aliasing, incomplete separation of signal and noise in the transform domain, and so on. Alternatively, model-based techniques have been developed. The techniques tyically implement surface-wave inversion to estimate an earth model, generate synthetic data from the model, and subtract the synthetic from seismic data. A high-resolution linear Radon transform can generate dispersion spectra from both seismic and synthetic data (Luo et al., 2008). Disperion curves, which express the relationship between frequences and corresponding phase velocities for different modes, can be extracted from the dispersion spectra. The inversion methods are widely developed to attenuate ground roll by matching the dispersion curves (Park et al., 1998; Douma et al., 2014). Due to the difficulties in identifying and picking the dispersion curves, Dou and Ajo-Franklin (2014) presented a method to directly match the dispersion spectra in the surface-wave inversion, while Groos et al. (2017) showed a method to minimize the misfit of the least-squares norm of normalized wavefields.

In this paper we present a model-based method to attenuate ground roll in prestack shot gathers. In the surface-wave inversion an optimal viscoelastic layered model is estimated through global and local optimization methods to minimize the misfit of dispersion spectra obtained from seismic and synthetic shot gathers. In order to mitigate the limitation of 1D modeling used in synthetic generation, adaptive subtraction filters are designed. The synthetic data are convolved with the filters and, then, are subtracted from the seismic data. Furthermore, we apply a multi-scale technique, i.e., series of optimization methods and adaptive subtraction are implemented several times. At each time ground roll is partly attenuated. The tests of 3D field data indicate that the method can effectively attenuate ground roll.

Method

Given a viscoelastic layered half-space model **m**, the misfit between the observed and model-predicted dispersion spectra is measured by an objective function J for a shot gather

$$J(\mathbf{m}) = \sqrt{\sum_{i=1}^{n_f}\sum_{j=1}^{n_v}(s_{ij}-o_{ij})^2/(n_f n_v)} \quad , \tag{1}$$

where o is the dispersion spectrum of the shot gather, s is the dispersion spectrum of the synthetic data obtained from **m**, n_f is the number of sampling points along the frequency axis, and n_v is the number of sampling points along the phase velocity axis in these dispersion spectra. It is noted that each spectrum is normalized by its maximum spectrum amplitude in order to preserve relative amplitudes.

In the model **m**, each layer is characterized by its thichness (h), P- and SV-wave velocities (V_p and V_s), density, P- and SV-wave quality factors (Q_p and Q_s). In the frequency domain the propagator solution from one layer to another, referred as a layer propagator, can be derived from the equation of movement (Aki and Richards, 1980). The eigenvalues and eigenvectors of a layer propagator result in the decomposition of up- and down-going P- and SV-waves and the computation of reflection and transmission coefficients at an interface between two layers. The propagator solution plus continuity conditions of reflection and transmission coefficients lead to a global matrix, known as propagator matrix method (Thomson, 1950; Haskell, 1953). Using free-surface boundary in the top layer and radiation condition in the bottom half space, particle displacements in each layer can be obtained from one layer to another for a vertical force or a point explosion. Particularly, a secular equation in the top layer can

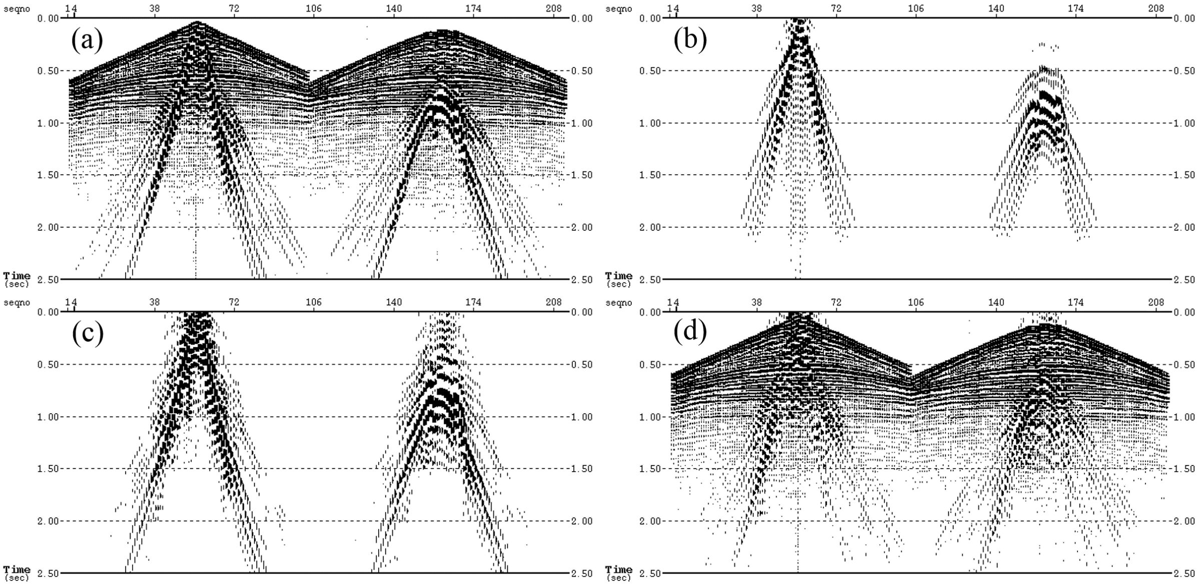

Figure 1: Surface-wave inversion and adaptive subtraction. (a) 2 receiver lines from a 3D shot gather. (b) Synthetic surface wave generated from an optimal model obtained by GA and simplex. (c) Convolution of synthetic surface wave with adaptive subtraction filters. (d) Ground-roll attenuation through the subtraction of panel (c) from panel (a).

give us phase velocities for each frequency and for each mode. Once the phase velocities are obtained, we can calculate Green's function at a receiver position to generate synthetic surface wave.

In this paper the inversion procedure is set as a bound-constrained optimization problem, for which we seek the optimal model **m** that minimizes the objective function J

$$\begin{aligned} &\text{minimize } J(\mathbf{m}) \\ &\text{subject to } m_i^l < m_i < m_i^u,\ i = 1, 2, \cdots, n \end{aligned} \quad , \tag{2}$$

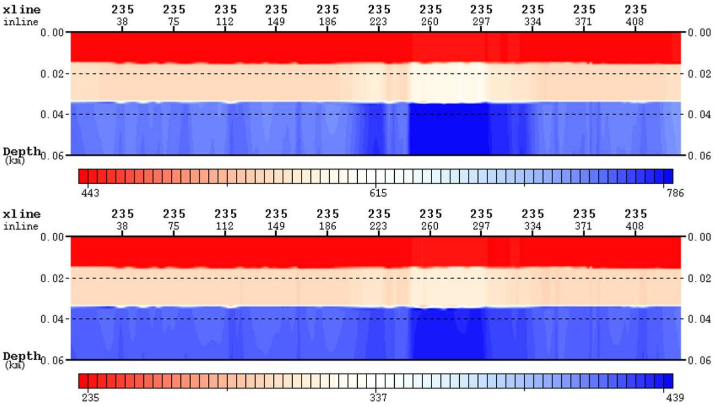

Figure 2: (top) V_p and (bottom) V_s obtained from surface-wave inversion.

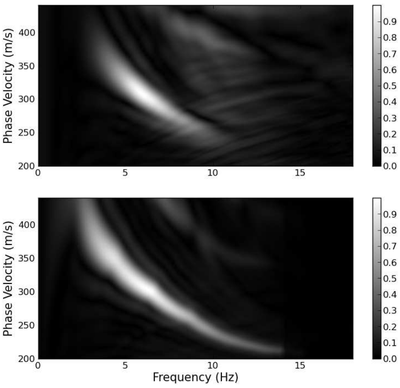

Figure 3: Dispersion spectra of (top) the gather in Figure 1(a) and (bottom) the gather in Figure 1(b).

where m_i is the i$^{\text{th}}$ parameter of a layered model **m**, m_i^l and m_i^u are the lower and upper bounds of m_i, repectively, and n is the number of parameters. For a r-layer model **m**, the updated parameters are listed as $\{h_1, V_1, \gamma_1, h_2, V_{s2}, \gamma_2, \cdots, h_i, V_{s,i}, \gamma_i, \cdots, h_{r-1}, V_{s,r-1}, \gamma_{r-1}, V_{sr}, \gamma_r\}$, where h_i is the thickness of the i$^{\text{th}}$ layer and γ_i is V_{pi}/V_{si}. Since surface-wave propagation is particularly sensitive to the S-wave properties, we prefer to upadte V_s. It is noted that V_1 can be either V_{p1} or V_{s1} in the 1st layer, and we do not update h_r in the bottom half space. Gardner's equation is used to calculate density for each layer (Gardner et al., 1974), and Q_p and Q_s are specified and are kept unchanged.

Because the inverse problem is nonlinear, the objective function can have multiple local minima. To avoid this limitation, genetic algorithm (GA) method is utilized (Whitley, 1994). GA is a derivative-free search approach toward globally optimal regions. Once the global optimization is achieved, the Nelder-Mead (NM) downhill simplex method is applied as an additional local-search enhancement to improve the optimal solution (Nelder and Mead, 1965). The simplex method is always applied after GA because GA can provide starting models necessary for the local search method.

The 1D model obtained from GA and simplex cannot represent any lateral variations of physical parameters. Adaptive subtraction filters can mitigate this limitation. We estimate least-squares matching filters for seismic and synthetic traces. A model-predicted trace is convolved with the matching filter and, then, subtracted from its corresponding data trace. In order to further mitigate the limitation of 1D layered model, multi-scale technique is applied. This means that series of GA, simplex and adaptive subtractions are implemented serevral times. Each time part of ground roll which fits the 1D model is removed.

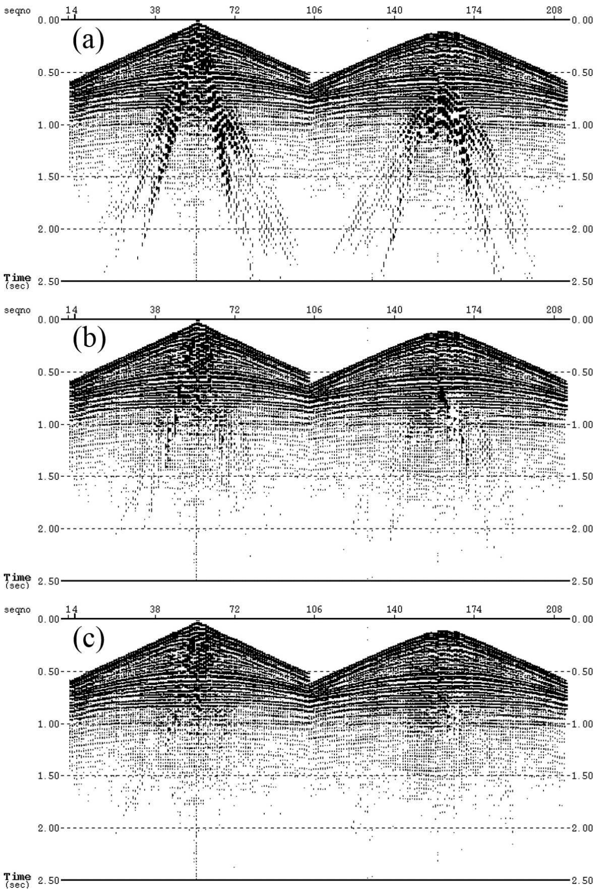

Figure 4: Surface-wave attenuation for the shot gather in Figure 1(a). Ground roll is continuously removed after the series of GA, simplex, and adaptive subtraction is implemented (a) 1, (b) 7 and (c) 14 times.

Examples

The proposed method is applied to a 3D seismic survey with 7616 shots. The sampling rate is 1 ms, and 3000 time samples/trace are recorded for each shot. Low-velocity, low-frequency and high-amplitude ground roll is observed (Figure 1(a)). The inversion procedure uses a 4-layer model and update V_s in the top layer. For each layer the thickness is limited between 3 and 30 meters, and both Q_p and Q_s are kept constant. A vertical force is applied to generate synthetic data with the maximum frequency of 18 Hz. 30-point filters are designed and applied in sliding windows of 150 ms for adaptive subtraction.

Table 1: V_s Bounds on the 1st Test

Layer	V_{min}(m/s)	V_{max}(m/s)
1	180	400
2	220	470
3	300	550
4	350	600

Table 2: V_s Bounds on the 2nd Test

Layer	V_{min}(m/s)	V_{max}(m/s)
1	50	600
2	75	650
3	100	700
4	150	800

In the inversion of the 1st test γ is limited between 1.5 and 2.2 in each layer, and the V_s bounds are listed in Table 1. GA has 50 generations and its population size is 500. Simplex implements 20 iterations. Figure 1(b) shows 10-mode synthetic surface wave generated from an optimal model. In general, the synthetic data matches the groun roll present in the seismic data. Matching filter further improves the similarity of the modeled and recorded surface waves (Figure 1(c)). Ground roll is significantly attenuated as a result of the adaptive subtraction (Figure 1(d)). Figure 2 shows the velocities obtained from the optimizations. The test shows that the method is able to find an optimal model to match the dispersion spectra (Figure 3) and, hence, generate the synthetic data suitable for gound-roll attenuation. Our tests indicate that increasing the generations and population of GA and the iterations of simplex can increase the accuracy of matching dispersion spectra. However, the increases can significantly increase computation cost.

On the 2nd test γ is limited between 1.3 and 5.2 in each layer, and the V_s bounds are listed in Table 2. GA has 8 generations and its population size per generation is 20. The series of GA, simplex and adaptive subtraction is implemented 14 times. Only the fundamental-mode synthetic data is generated. Figure 4 shows that ground roll is gradually removed through iterations. In Figure 4(b) most ground roll is removed after 7 iterations. At the end of 14 iterations, ground roll is almost completely removed (Figure 4(c)). Since multi-scale technique is applied, the accuracy requirements for matching dispersion spectra are not high. This means that a small number of models can be evalued in the inversion and, hence, the cost can be significantly reduced. This test demonstrates that the method is robust and can efficiently remove surface waves in practice.

Conclusions

In this paper we present a method, which includes surface-wave inversion and adaptive subtraction via a multi-scale technique, in order to attenuate ground roll in prestack seismic data. The GA and simplex methods can find an optimal viscoelastic layered model for matching disperion spectra in surface-wave inversion. The synthetic surface wave obtained from the optimal model is then subtracted from the recorded data via adaptive subtraction. The tests indicate that the adaptive subtraction and multi-scale technique make this method robust and efficient in attenuating ground roll for field data.

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