Determining Scale Properties from Seismic Transmission Responses: A Modeling Study

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Summary

Seismic imaging methods have been valuable in probing the earth's subsurface. The image quality obtained of target structures is subject to the scattering effects by subsurface heterogeneities (scale, size, composition) on the wavefield recorded at the 3C sensors. Our modeling study suggests that the spectral content of the forward scattered energy (transmitted wave) can provide information on medium properties (ΔV_p, ΔV_s, $\Delta\rho$, and scale length). Accounting for these scattering effects via deconvolution and statics processing routines can help improve the quality of surface and borehole seismic images.

Introduction

Seismic scattering has been studied for over two decades by exploration and earthquake seismologists. In an exploration setting, the impedance contrast between target structures and background as well as near surface statics due to weathering influence the quality of the seismic reflection image. In hardrock environment for example, the inhomogeneities (perturbations in elastic properties) existing in the background medium pose a severe problem to adequately image reflections from targets (ore body). The perturbations in velocity and density are responsible for fluctuations in the amplitudes, traveltime and phase distortions observed in the seismic waves. Wu (1989) classified the scattering effects by various scale heterogeneities into different propagation regimes:

a) Quasi homogeneous; when the heterogeneities are too small to be seen by the waves.
b) Rayleigh scattering; which can cause apparent attenuation.
c) Mie scattering; where the size of the heterogeneities are comparable to the wavelength.
d) Small angle scattering; where the scattering power is concentrated in the forward direction.

The frequency distortions due to scattering can be useful to estimate scale characteristics of the inhomogeneities intercepted by the wavefield. Here we investigate forward scattered energy, which include direct arrivals, converted energy and coda. The principal causes of frequency fluctuations are multiples and energy redistribution which result in interferences causing amplification/attenuation of certain frequencies (resonance scattering, Wu, 1989; Milkereit et al., 2003). Geometries of interest include cases with sharp impedance contrast (overburden effect) and those with defined target structures (**Figure 1**).

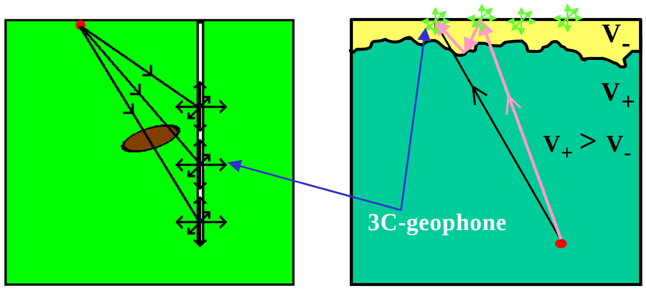


Figure 1: Geometry illustrating scattering by limited target (left panel), and the case of overburden (right panel, large reflection coefficient R).

Method and Results

The forward scattered energy can be viewed as a transmission response. For layered medium, there exist a vast literature that emphasizes the amplitude and spectral characteristics of the transmitted energy (Claerbout, 1968, O'Doherty and Anstey, 1971). The amplitude spectrum of the transmitted energy recorded at the receiver site can be formulated mathematically as:

$$A(f) = S_0(f)P(f)T(f) + n(f) \quad \textbf{(1)}$$

and travel time delays in terms of the phase shifts as $\delta\phi = 2\pi f\,\delta t$

where, $T(f)$ represents the amplitude spectra of the transmission impulse responses characterizing the medium of propagation, $S_0(f)$ is the spectrum of the source signature, $P(f)$ is the path effect (geometric spreading, reflection losses), $n(f)$ is the background noise, f is the frequency, ϕ is the phase and t is the time. In theory, Equation (1) suggests scattering can be corrected for by estimating and deconvolving $T(f)$ from recorded seismic traces. In this modeling study we investigate how scattering effects cause alterations in frequency and phase spectra and how this could be related to scale lengths.

a) A simple 1D-Model

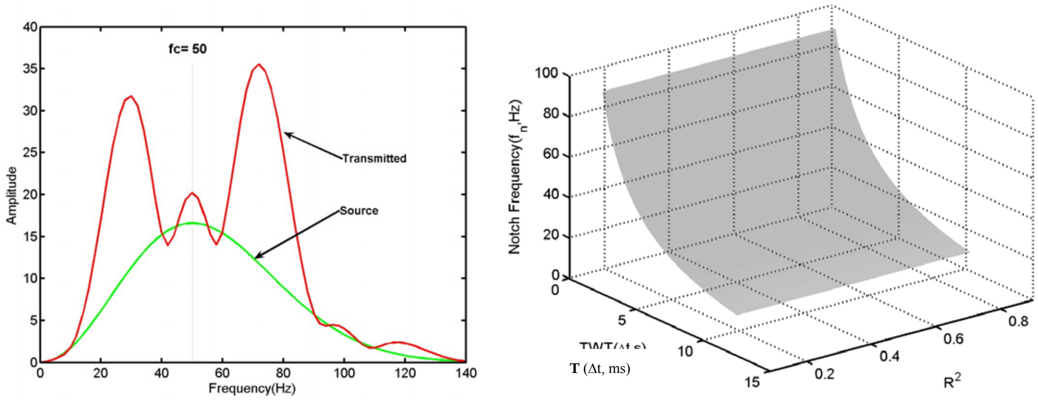
1D-modeling asseses the role of multiples, magnitude of the reflection coefficient (R), and layer thickness (vertical scale length) in distorting the frequency content (e.g by creating notches at certain frequencies) when interfering with direct arrivals. The 1D models demonstrate that layering suffices to create these multiples. **Figure 2a** shows the effect of multiples created by reverberations within the overburden layer (overburden effect). Notice the amplification of frequencies other than the dominant frequency of the source wavelet (ricker wavelet).

Though multiples distort spectral content, the overall extent of this effect depends on the kind of medium encountered. Consider the case of a simple 3-layered medium (a single layer sandwiched by a background medium). Let us assume that the ratio of the reflected to incident amplitude at the intermediate layer is R(reflection coefficient). For a 1D synthetic transmission using a ricker wavelet, the ratio between the direct arrival and multiples will be $1/R^{2n}$ (n: nth multiple) with the multiples having time lags of $n\Delta t$ (Δt: two-way travel time within the intermediate layer) with respect to the direct arrivals. Significant alteration in the amplitude spectrum (e.g. creation of notches) due to interference from multiples is not apparent unless R> 0.4 (R>=0.3 when using spectral ratios with respect to source spectrum). Notch frequencies are independent of R and the source spectrum but are dependent on the thickness of the intermediate layer (**Figure 2b**) whereby :

$$f_n = V / 4a_Z \quad \textbf{(2)}$$

V: layer velocity, a_z: vertical scale length (layer thickness), and f_n: notch frequency

It is worth noting that the consistent results obtained in this 1D assessment are from an idealized approach. However, this may not apply if other factors like spherical divergence, incidence angle, multiple layering, wave conversion, intrinsic attenuation and background noise are considered.



a) b)

Figure 2: **a)** Amplitude spectrum of transmitted energy in two-layered medium illustrating the overburden effect: gneiss (5933 m/s, 2722 kg/m^3) and clay overburden (2000m/s, 2000 kg/m^3, 20m thick). Analysis is based on normal incidence. The transmitted trace consists of the direct arrival and two multiples.

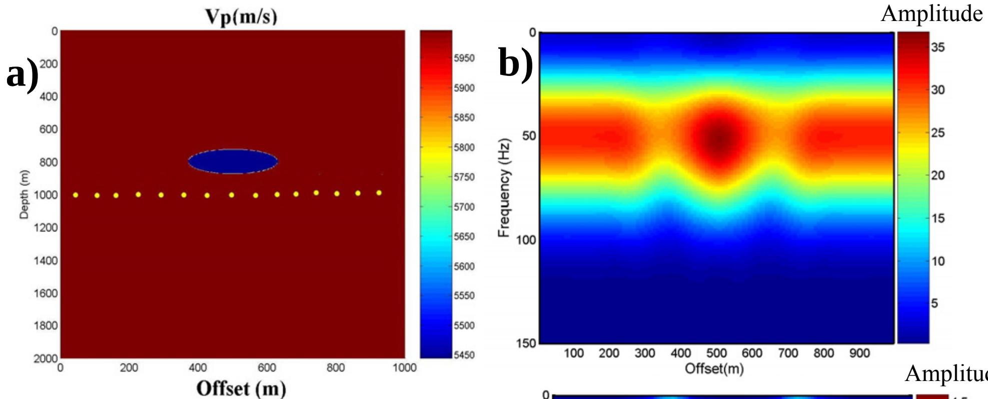
b) Relation between intermediate layer thickness ($\Delta t \; \alpha \; a_z$), reflection coefficient (R), and notch frequency (f_n) for a 3-layered medium. Ricker wavelet source frequencies used include: 40Hz, 50Hz, 70Hz, and 80Hz. The plot is done using R^2 given that we are considering the effect of the first multiple to have the most impact in spectral distortion due to interference.

b) 2D- Model

Modeling was done using a 2D finite difference viscoelastic code (Bohlen, 2002). Solving for the total wavefield via finite difference method provides a more realistic basis for assessing forward scattering caused by heterogeneities (ΔV_p, ΔV_s, $\Delta\rho$) since factors such as energy conversion and angle dependent redistribution of energy are accounted for, unlike the 1D case. The 2D model used includes a single lens (sulfide ore) in a homogenous background. In order to simplify our analysis, we used a plane wave source with a dominant frequency of 50Hz. For reasons related to waveform healing phenomenon of scattered seismic waves with distance, we measured the scattered wavefield at positions within one wavelength of the lens inclusion. **Figure 3** shows the spectral decomposition of windowed first break events from the vertical and horizontal components of the transmitted wavefield. The presence of energy on the horizontal component (<20 %) provides key information on the presence of a scatterer. Spectral ratios of the horizontal to the vertical component can provide information on amplified/attenuated frequencies, which in turn can be correlated to scale length. Owing to the large discrepancy in the energy content between the respective components, adequate methods for analyzing these spectral ratios need to be developed.

Conclusions

We have demonstrated through 1D and 2D forward modeling that the frequency content of forward scattered energy contains valuable information for characterizing medium scale parameters. Considering the results of the 2D modeling study and given that the earth is 3D, spectral analysis of 3C- geophone data looks promising for obtaining scale information of the medium. For such analysis, 3C broadband seismic recordings are required for assesing scale length properties at depth (Vertical Seismic Profiling:VSP) and for characterizing near surface heterogeneities (statics). Future work will aim at designing methods for adequately analyzing the spectral content of the transmitted response and how these correlate with medium scale parameters. Modeling studies that will include explosive sources and wave propagation in homogenous, layered and random media will also be considered.



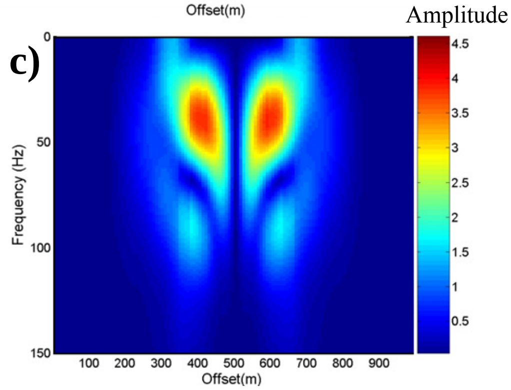


Figure 3: **a)** Petrophysical model with sphalerite lens inclusion (a_{zlens}=150m). The yellow line represents the receiver locations; **b)** and **c)** show the amplitude spectrum of windowed first arrivals of the vertical and horizontal components respectively.

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