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3-D Acoustic Green's Function Modeling in Multilayered Overburden

M. Ayzenberg* (Norwegian University of Science & Technology), A. Aizenberg (Institute of Petroleum Geology and Geophysics), H. Helle (Odin Petroleum), K. Klem-Musatov (Institute of Petroleum Geology and Geophysics), J. Pajchel (Norsk Hydro) & B. Ursin (Norwegian University of Science & Technology)

SUMMARY

We present an analytic approach to the description and modeling of the 3-D acoustic waves in complex multilayered overburden. The total scattered wavefield is split into a branching sequence of multiply reflected/transmitted wavefields which can be directly identified with the intermediate reflectors generating them. Each wavefield is represented by a combination of surface integral propagators and effective reflection/transmission coefficients. The synthetic modeling results show that the approach enables preserving of the kinematic and dynamic properties of multiply scattered wavefields, and in particular the Green's function, in overburden with strong-contrast and strongly-curved intermediate reflectors.

Introduction. Seismic image resolution below a complex overburden is an actual problem of today. The improvement of the resolution strongly depends on the quality of modeling of the Green's function, which is the basis of many migration and inversion algorithms (Ursin, 2004). In particular, a correct description of the amplitude and phase is required. To help solving the problem, we propose an analytic approach to description and modeling of the 3-D Green's function in accordance to the geological structure of the overburden. The approach is based on splitting the total wavefield into a branching sequence of wavefields, each representing a wave multiply reflected/transmitted in accordance to its own wavecode. Such a wave is the result of the action of the composition of long-distance surface integral propagators and effective reflection/ transmission coefficients over the source wavefield. Synthetic modeling of the 3-D Green's function in a model with strongly varying geometry and overburden parameters shows that the approach is capable of reproducing complex wavefields in a way that preserves kinematics and dynamics.

Theory. We consider scattering of acoustic waves in a 3-D multilayered overburden with smoothly curved interfaces. Each layer is described by a velocity c and density ρ. The total pressure wavefields represent a solution of an acoustic transmission problem, which is described by the acoustic wave equations inside the layers, radiation conditions at the infinity, and the conditions of the continuity of the wavefields and corresponding normal accelerations at the interfaces. Assume a source of acoustic pressure wave be positioned at a point x^s.

To solve this problem analytically, we rewrite the interface conditions in an equivalent convolution form of a reflection/transmission transform and obtain a modified statement of the transmission problem (Klem-Musatov et al., 2005; Aizenberg et al., 2006b). Application of the direct boundary integral equation method to this problem gives a modified system of the boundary integral equations of the second type. The Neumann iterative method generates its exact analytic solution in the form of the branching set of events multiply reflected/transmitted in accordance with their wavecode. It is essential that such a representation of the solution does not experience problems of convergence and uniqueness, since each event describes its own wavecode and can not be corrected by other ones.

Using the analytical representation of the exact solution, the total scattered acoustic pressure wavefield $p\left(\mathrm{x}^r\right)$ recorded at a point x^r is represented by the sum,

$$p\left(\mathrm{x}^r\right)=\sum_{i\in\{wavecodes\}} p_i\left(\mathrm{x}^r\right).$$

Here $p_i\left(\mathrm{x}^r\right)$ is a wavefield multiply reflected/transmitted in accordance to the wavecode having number i, which belongs to the set of all possible wavecodes for the chosen overburden model. Each multiply reflected/transmitted wavefield is represented by a combination of long-distance surface integral propagators inside layers and reflection/transmission operators when crossing interface, acting over the incident wavefield (Figure 1).

The propagator from an intermediate interface S to any point x, which either belongs to a neighboring interface or coincides with the receiver point x^r, is described by a Kirchhoff-type integral,

$$\mathrm{P}\left(\mathrm{x},\mathrm{x}'\right)=\iint_S \frac{1}{\rho\left(\mathrm{x}'\right)}\left[\frac{\partial}{\partial n} g\left(\mathrm{x},\mathrm{x}'\right)-g\left(\mathrm{x},\mathrm{x}'\right)\frac{\partial}{\partial n}\right] dS\left(\mathrm{x}'\right),$$

where $g\left(\mathrm{x},\mathrm{x}'\right)$ is the Green's function in the layer, and n is the normal to S. For numerical simulation, a high-frequency approximation of the propagators is realized in the form of the multiple tip wave superposition method (Klem-Musatov and Aizenberg, 1985; Klem-Musatov et al., 2005). The method has proved to be capable of correct reproducing such complex wave phenomena as caustics and diffractions.

The reflection/transmission operators are,

$$\mathrm{R}(\mathrm{x}) = F^{-1}\,\hat{\mathrm{R}}(k)\,F, \quad \mathrm{T}(\mathrm{x}) = F^{-1}\,\hat{\mathrm{T}}(k)\,F,$$

where $\hat{\mathrm{R}}(k)$ and $\hat{\mathrm{T}}(k)$ are the plane-wave reflection/transmission coefficients, F is the Fourier transform from the curvilinear interface S to the plane of the wavenumbers (k_1, k_2), F^{-1} is the inverse Fourier transform to the point x, and $k = \sqrt{k_1^2 + k_2^2}$ (Aizenberg et al., 2006a). For numerical simulation, the reflection/transmission operators are reduced to a high-frequency approximation in the form of the effective reflection/transmission coefficients (Ayzenberg et al., 2006). We have shown that they account for the local interface curvature, the wavefront curvature and the dominant frequency of the source wavefield. They correctly describe the near- and super-critical phenomena, in particular the head-waves. The effective reflection coefficient (ERC) for various linear dominant frequencies f is shown in Figure 2. For comparison, we provide the plane-wave reflection coefficient (PWRC).

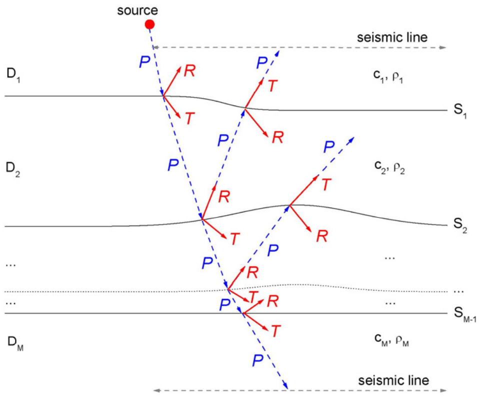

Figure 1: *The action of the propagators and reflection/transmission operators.*

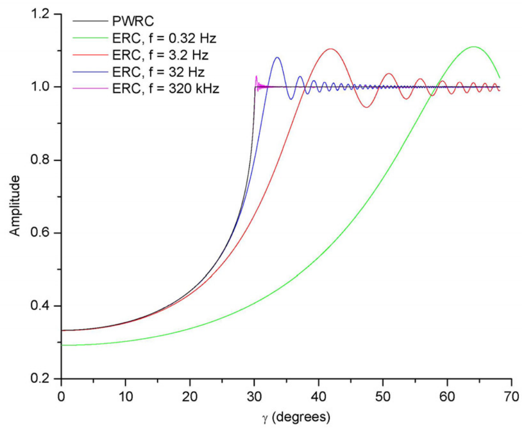

Figure 2: *The effective reflection coefficient.*

Synthetic modeling. As an illustration of the approach, the synthetic modeling of the 3-D Green's function was performed using the multiple tip wave superposition method with effective reflection/transmission coefficients (Aizenberg et al., 2006a; Ayzenberg et al., 2006). The modeling is done with a sine-like wavelet having the dominant frequency of $f = 22\ Hz$. The velocity and density model and interface geometry is chosen to be similar to the geological structures found in the Gulf of Mexico (Table 1) (Ogilvie and Purnell, 1996). The source is positioned at a point $\mathrm{x}^s = (0,0,0)\ km$. A flexure-type seabed changes from a depth of $1\ km$ to a depth of $1.2\ km$. A top of salt is placed at $2.8\ km$ and has a Gaussian anticline of $300\ m$. A top of the gas-filled reservoir is at $3.7\ km$ and has a Gaussian anticline of $100\ m$. A bottom of the reservoir is chosen to be flat at $4\ km$.

Layer	**Velocity, m/s**	**Density, g/cm^3**
Sea water	1500	1
Sandstone	2400	2.1
Salt	4500	2.6
Gas-saturated sandstone	2000	2.0
Shale	2400	2.25

Table 1: *The velocities and densities for synthetic modeling.*

To demonstrate the ability of modeling multiply scattered waveevents, we chose three numerical tests (Aizenberg et al., 2006b). First we place 101 equally spaced receivers with a step of $20\,m$ at a depth of $3.5\,km$ to record a primary sub-salt arrival, which can be interpreted as the Green's function for migration purposes. The wavecode (P2) and the seismogram are shown in Figure 3. The test clearly shows the ability of the approach to reproduce multipathing arrivals. Next we place the same receiver array at a depth of $4.8\,km$ to record the primary arrival from the whole stack of layers. The wavecode (P4) and the seismogram are shown in Figure 4. Thus we observe the wavefield development with depth. Our last test is devoted to obtaining the complete seismogram containing all scattered events which arrive within the time window $t < 3.8\,s$. There appeared to be five possible events, one of them containing a multiple reverberation inside the salt layer. The events are modeled independently and afterwards combined to produce the complete seismogram in Figure 5. Notice that the reflections with the wavecodes C4 and C5 arrive at close times. In this particular case the ability of modeling these two events separately simplifies interpretation of the modeling results.

Conclusions. We have presented an analytic approach to the description and modeling of the 3-D acoustic Green's function in multilayered overburden. The total wavefield is split into the branching sequence of multiply reflected/transmitted waves. Each of them is represented in terms of the surface integral propagators and reflection/transmission operators. The results of the synthetic modeling using the multiple tip wave superposition method with effective coefficients show that the approach enables preserving of the kinematic and dynamic properties of the Green's function.

Acknowledgements. The authors thank the O&E Research Centre of Norsk Hydro (Bergen, Norway) for support of this study.

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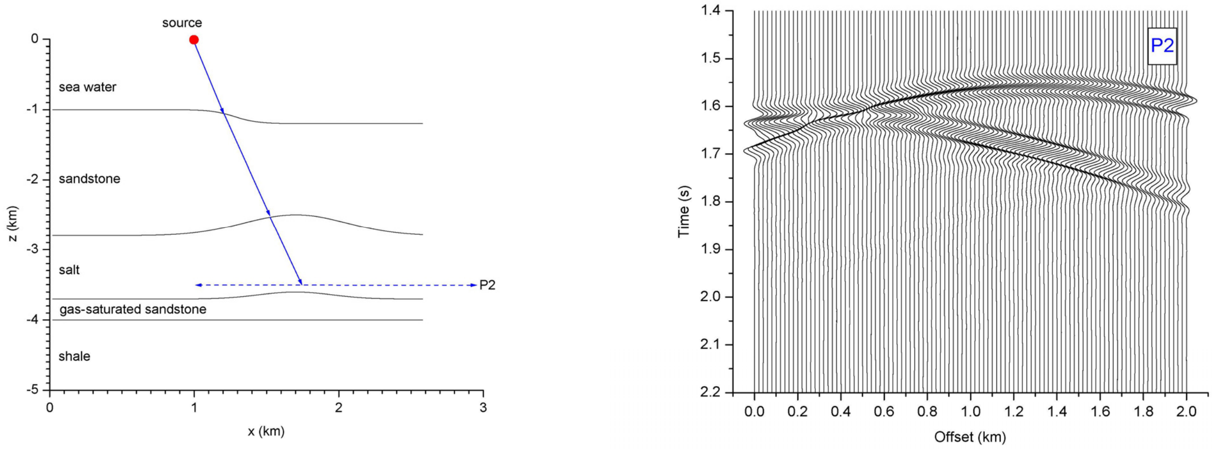

Figure 3: *The wavecode and seismogram for the sub-salt transmission.*

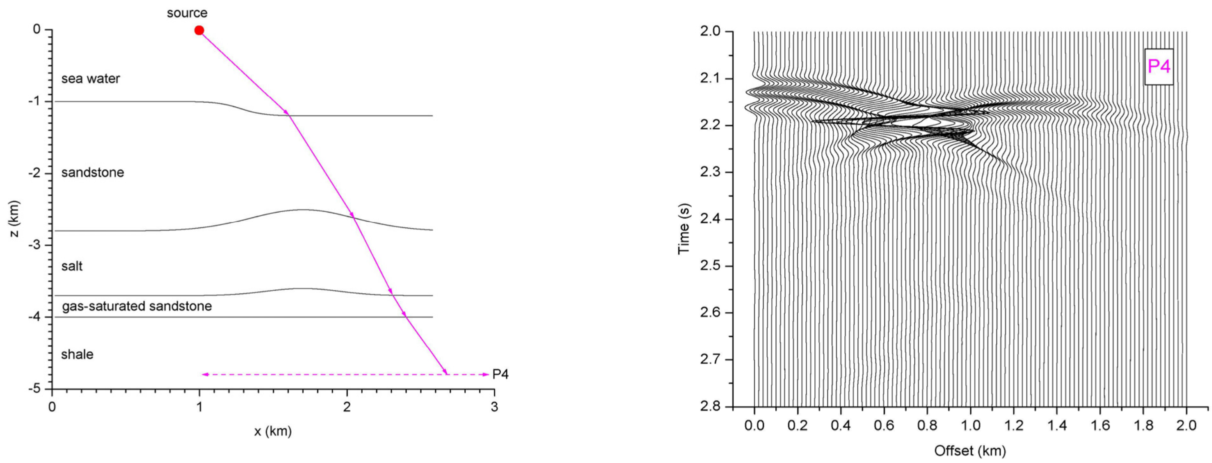

Figure 4: *The wavecode and seismogram for the transmission below bottom of the reservoir.*

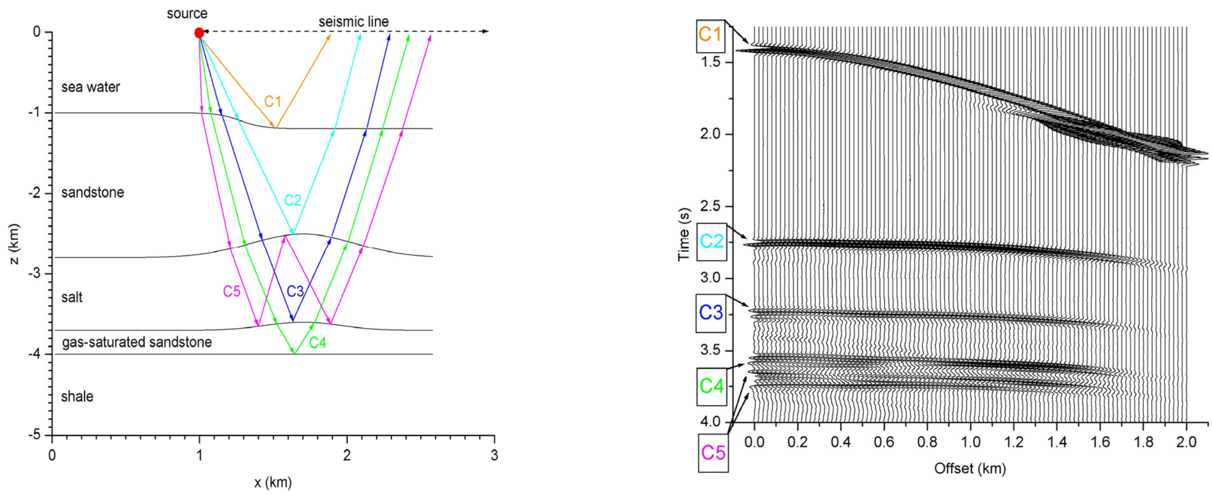

Figure 5: *The wavecodes and complete seismogram for the reflection from the overburden.*