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Application of conditional simulation of heterogeneous rock properties to seismic scattering and attenuation analysis in gas hydrate reservoirs

Jun-Wei Huang [a,*], Gilles Bellefleur [b], Bernd Milkereit [a]

[a] University of Toronto, 60 St. George Street, Toronto ON, Canada M5S 1A7
[b] Geological Survey of Canada, 615 Booth Street, Ottawa ON, Canada K1A 0E9

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ABSTRACT

We present a conditional simulation algorithm to parameterize three-dimensional heterogeneities and construct heterogeneous petrophysical reservoir models. The models match the data at borehole locations, simulate heterogeneities at the same resolution as borehole logging data elsewhere in the model space, and simultaneously honor the correlations among multiple rock properties. The model provides a heterogeneous environment in which a variety of geophysical experiments can be simulated. This includes the estimation of petrophysical properties and the study of geophysical response to the heterogeneities. As an example, we model the elastic properties of a gas hydrate accumulation located at Mallik, Northwest Territories, Canada. The modeled properties include compressional and shear-wave velocities that primarily depend on the saturation of hydrate in the pore space of the subsurface lithologies. We introduce the conditional heterogeneous petrophysical models into a finite difference modeling program to study seismic scattering and attenuation due to multi-scale heterogeneity. Similarities between resonance scattering analysis of synthetic and field Vertical Seismic Profile data reveal heterogeneity with a horizontal-scale of approximately 50 m in the shallow part of the gas hydrate interval. A cross-borehole numerical experiment demonstrates that apparent seismic energy loss can occur in a pure elastic medium without any intrinsic attenuation of hydrate-bearing sediments. This apparent attenuation is largely attributed to attenuative leaky mode propagation of seismic waves through large-scale gas hydrate occurrence as well as scattering from patchy distribution of gas hydrate.

1. Introduction

Reservoirs are rarely defined by a single variable and their characterization usually requires a variety of geophysical techniques, each sensing different rock properties. Depending on the sensing techniques, each measured rock property will provide a different image of the reservoir with a different imaging scale. For example, conventional seismic surveys image elastic properties at ~10–100 m scales, whereas well logs can measure rock properties at the scales <10 m. A variety of literature has been devoted to parameterization of multi-dimensional heterogeneities at different scales determined by various types of measurement. In seismology, Holliger and Levander (1992) and Holliger et al. (1993) used covariance functions to statistically characterize digitized geological maps and constructed a model that qualitatively explained lithospheric heterogeneities observed on crustal-scale seismic data. Hurich and Kocurko (2000) also analyzed geologic variations using a 2D von Kármán power spectrum function and attempted to correlate the statistical properties of geology with the complexity, scaling characteristics and spatial variability of seismic reflection data. Goff and Holliger (1999) established that velocity fluctuations on well logs from the upper crust provided indications for the superposition of four stochastic processes with different characteristic scales, each explained and described by a von Kármán function. The aforementioned studies focused on continental-scale heterogeneities in the earth medium. At the reservoir scale, Hewett (1986) was among the first in discussing the statistical properties of hydrocarbon reservoir heterogeneities. Stefani and De (2001) analyzed a wide range of vertical and horizontal well logs and observed the same statistical characteristics in reservoir scale well logs as in crustal logs (Goff and Holliger, 1999). Huang et al. (2009) demonstrated the applicability of spectral-based simulation method to characterize heterogeneity of hydrate-bearing sediments honoring different correlation coefficients between multiple rock properties inferred from collocated well logs. They constructed petrophysical reservoir models to estimate hydrate volume as well as to simulate elastic seismic wave propagation and thus potentially provided a link between seismic expressions of heterogeneities to volume of hydrate in the pore space of poorly consolidated sediments. A significant limitation of their study was that a nonconditional simulation method was employed so that the reservoir models were unable to represent the

* Corresponding author at: Vibrometric Canada Limited, 425 Adelaide St West, Suite 702, Toronto, ON, Canada M5V 3C1. Tel.: +1 416 348 9199; fax: +1 416 348 0399.
E-mail address: junwei.huang@vibrometric.com (J.-W. Huang).

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spatial variability of field observations and measurements. In this study, we extend the nonconditional simulation method used in Huang et al. (2009) to a conditional simulation method.

Chilès and Delfiner (1999) describe a variety of conditional simulation methods of continuous random functions that have been developed. These include Sequential Gaussian (e.g., Alabert and Massonnat, 1990), Matrix Decomposition (Davis, 1987), Turning Bands (Matheron, 1973), and Discrete Spectral methods (Shinozuka, 1987). Sequential Gaussian and Matrix Decomposition methods can directly condition the model with measurements, whereas others such as Turning Band and Discrete Spectral methods must employ an additional kriging step to honor the data (Delfiner, 1976; Journel, 1974). We follow the spectral-based simulation method initially used in Huang et al. (2009). One advantage of the spectral-based method over others is the computation efficiency inherited from Fast Fourier Transform (FFT). It can simulate an arbitrary number of points in multiple dimensions for a large range of covariance in a timely manner. Although one more step of kriging must be followed to condition the model with observations, both the simulation and kriging procedures can be easily implemented on current parallel architectures for large reservoir models. In contrast, random path-based sequential procedures cannot be easily parallelized on current parallel architectures. For example, Mariethoz (2009) provided a parallelization strategy for random path based geostatistical simulation methods on distributed memory architectures, but the algorithm sacrificed the reproducibility of the simulated results. Another advantage of the spectral method is that the cross correlation between multiple parameters can be handled in the wave number domain by a cross-spectral density matrix (Huang et al., 2009; Shinozuka, 1987) during the nonconditional simulation.

In this paper, we provide a brief review of the theory of spectral-based conditional simulation. We then present a step-by-step algorithm to construct multi-variate heterogeneous geophysical models from borehole logs. Then, we apply this algorithm to a gas hydrate reservoir near the Mallik research well site, Northwest Territories, Canada. The petrophysical models of hydrate-bearing sediments are tied with well logs and are used subsequently in a finite difference modeling program to study the impact of multi-scale heterogeneous gas hydrate distribution on seismic wave behaviors in vertical seismic profiling (VSP) and cross-borehole geometry. We show that seismic scattering and attenuation produced by heterogeneity can explain observations on field VSP and crosshole seismic data acquired in hydrate-bearing sediments.

2. Methodology

2.1. Spectral-based nonconditional simulation

In general, a univariant stationary stochastic field can be characterized by a Probability Density Function (PDF) and an autocorrelation function (ACF) which can be Fourier transformed to determine the Power Spectrum Density Function (PSDF). For a multi-variate process, a cross-spectra density matrix must be used instead of a single PSDF to honor the mutual statistical correlations between variables. The detailed mathematic expressions needed to simulate a multi-dimensional and multi-variate stochastic field can be found in Shinozuka (1987), and Huang et al. (2009, 2011).

For a three-dimensional (3D) and three-variant (3V) problem of essential interest in our study, a 3×3 cross-spectra density matrix $\mathbf{S}(\mathbf{k})$ can be assembled from the power spectral density functions of three variants, i.e., $S_{uu}(\mathbf{k})$ of P-wave velocity v_p, S-wave velocity v_s, and density ρ:

$$\mathbf{S}(\mathbf{k})=\begin{bmatrix} S_{pp}(\mathbf{k}) & S_{ps}(\mathbf{k}) & S_{pr}(\mathbf{k}) \\ S_{sp}(\mathbf{k}) & S_{ss}(\mathbf{k}) & S_{sr}(\mathbf{k}) \\ S_{rp}(\mathbf{k}) & S_{rs}(\mathbf{k}) & S_{rr}(\mathbf{k}) \end{bmatrix}, \tag{1}$$

where S_{pp}, S_{ss}, and S_{rr} are PSDF of auto-correlation functions of v_p, v_s, and ρ, respectively and $\mathbf{k}=[k_x, k_y, k_z]^T$. The other PSDF are the cross-correlations between v_p, v_s, and ρ. For the 3D case, assuming that all variants are correlated with each other, i.e., none PSDF in Eq. (1) vanishes, the 3D–3V models can be simulated from

$$\begin{aligned}
v_p^{sim}(\mathbf{x}) &= \frac{1}{(2\pi)^{\frac{3}{2}}}\sum_{i=-N_x}^{N_x}\sum_{j=-N_y}^{N_y}\sum_{k=-N_z}^{N_z}\sqrt{\left|S_{pp}\right|\Delta k_x\cdot\Delta k_y\cdot\Delta k_z}\cdot\cos\left(k_{xi}x+k_{yj}y+k_{zk}z+\theta_{11}+\Phi_{1ijk}\right)\\
v_s^{sim}(\mathbf{x}) &= \frac{1}{(2\pi)^{\frac{3}{2}}}\sum_{i=-N_x}^{N_x}\sum_{j=-N_y}^{N_y}\sum_{k=-N_z}^{N_z}\sqrt{\left|\frac{S_{ps}^2}{S_{pp}}\right|\Delta k_x\cdot\Delta k_y\cdot\Delta k_z}\cdot\cos\left(k_{xi}x+k_{yj}y+k_{zk}z+\theta_{21}+\Phi_{1ijk}\right)\\
&\quad+\frac{1}{(2\pi)^{\frac{3}{2}}}\sum_{i=-N_x}^{N_x}\sum_{j=-N_y}^{N_y}\sum_{k=-N_z}^{N_z}\sqrt{\left|S_{ss}-\frac{S_{ps}^2}{S_{pp}}\right|\Delta k_x\cdot\Delta k_y\cdot\Delta k_z}\cdot\cos\left(k_{xi}x+k_{yj}y+k_{zk}z\right.\\
&\quad\left.+\theta_{22}+\Phi_{2ijk}\right)\\
\rho^{sim}(\mathbf{x}) &= \frac{1}{(2\pi)^{\frac{3}{2}}}\sum_{i=-N_x}^{N_x}\sum_{j=-N_y}^{N_y}\sum_{k=-N_z}^{N_z}\sqrt{\left|\frac{S_{pr}^2}{S_{pp}}\right|\Delta k_x\cdot\Delta k_y\cdot\Delta k_z}\cdot\cos\left(k_{xi}x+k_{yj}y+k_{zk}z+\theta_{31}+\Phi_{1ijk}\right)\\
&\quad+\frac{1}{(2\pi)^{\frac{3}{2}}}\sum_{i=-N_x}^{N_x}\sum_{j=-N_y}^{N_y}\sum_{k=-N_z}^{N_z}\sqrt{\left|\frac{\left(S_{sr}-\frac{S_{ps}S_{pr}}{S_{pp}}\right)^2}{S_{ss}-\frac{S_{ps}^2}{S_{pp}}}\right|\Delta k_x\cdot\Delta k_y\cdot\Delta k_z}\cdot\cos\left(k_{xi}x+k_{yj}y\right.\\
&\quad\left.+k_{zk}z+\theta_{32}+\Phi_{2ijk}\right)\\
&\quad+\frac{1}{(2\pi)^{\frac{3}{2}}}\sum_{i=-N_x}^{N_x}\sum_{j=-N_y}^{N_y}\sum_{k=-N_z}^{N_z}\sqrt{\left|S_{rr}-\frac{S_{pr}^2}{S_{pp}}-\frac{\left(S_{sr}-\frac{S_{ps}S_{pr}}{S_{pp}}\right)^2}{S_{ss}-\frac{S_{ps}^2}{S_{pp}}}\right|\Delta k_x\cdot\Delta k_y\cdot\Delta k_z}\cdot\cos\left(k_{xi}x\right.\\
&\quad\left.+k_{yj}y+k_{zk}z+\theta_{33}+\Phi_{3ijk}\right),
\end{aligned} \tag{2}$$

where $|\,.\,|$ is the absolute value operator. In case where the value inside the operator is complex, the corresponding θ_{im} is the argument and non-zero by default. Parameters k_{xi}, k_{yj}, k_{zk} are the discrete wavenumbers, and Δk_x Δk_y Δk_z are the wavenumber intervals in x, y and z dimensions, respectively. Parameters Φ_1, Φ_2, and Φ_3 are three independent random phases uniformly distributed from 0 to 2π. For simplicity, the dependence of PSDF and θ_{im} on wavenumber is dropped.

The PSDFs of sonic logs from Mallik show power law features (Holliger, et al. 2003; Mandelbrot, 1983) with a corner wave number related to the characteristic scale in the medium (Fig. 1). This type of power spectrum density function can be characterized by a von Kármán spectral density function (von Kármán, 1948). Fig. 2 shows an example of a von Kármán PSDF of a stochastic medium with a unit standard deviation (σ) and a 10 m isotropic characteristic scale or correlation length ($a=a_x=a_y=10$ m). The corner wave number is close to 0.1 m^{-1} ($=1/a$). The function behaves as an asymptotic power law at wave numbers larger than 0.1 m^{-1}. In this study, we fit the data with the von Kármán correlation function using nonlinear regression, and use the von Kármán PSDF to simulate heterogeneities within hydrate-bearing sediments as outlined in Eq. (2). The Hurst number and vertical characteristic scale (a_z) can be estimated from borehole logs whereas the lateral characteristic scales (a_x and a_y) must be estimated from external sources such as reflection images from surface, VSP, and cross-borehole seismic data.

The von Kármán covariance function is analytically expressed as (Goff and Jordan, 1988):

$$C(r(\mathbf{x}))=(1-(1-\delta_r)n_0)\frac{r^{\nu}K_{\nu}(r)}{2^{\nu-1}\Gamma(\nu)},\ r(\mathbf{x})=\sqrt{\left(\frac{x}{a_x}\right)^2+\left(\frac{y}{a_y}\right)^2+\left(\frac{z}{a_z}\right)^2}, \tag{3}$$

where n_0 accounts the nugget effect (the discontinuity at $r=0$), δ_r is a Kronecker delta, ($\delta_r=1$ when $r=0$, and $\delta_r=0$ when $r\neq0$), $K_{\nu}(r)$ is the modified Bessel function of the second kind, $\Gamma(\nu)$ is the Gamma