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Travel-time analyses in velocity structures composed of small- and large-scale inhomogeneities: Toward a combination of deterministic and stochastic approaches

T. Saito (1), O. Nishizawa (1) and T. Yokota (1)

(1) National Institute for Advanced Industrial Science and Technology, Japan

Travel-time tomography deterministically reconstructs subsurface velocity structures, where the resolution is limited by observation geometry and seismic wavelength. When the ray theory is employed, the minimum size resolvable becomes larger than the wavelength. On the other hand, subsurface velocity structure contains small-scale inhomogeneity of which scale is smaller than the wavelength. Because wave phenomena in such media are quite complicated, seismologists have attempted to estimate the inhomogeneity with stochastic approaches (e.g. Sato & Fehler 1998). Toward a combination of deterministic and stochastic approaches for the estimation of inhomogeneous structure, this study investigates the travel-time and residual in the inhomogeneous structures composed of large- and small-scale inhomogeneities.

An inhomogeneous velocity structure mentioned above is written as $V(x) = V_0(x)\{1+\xi(x)\}$ where large scale inhomogeneity $V_0(x)$ is deterministically given and small-scale inhomogeneity $\xi(x)$ is stochastically given by a random function of location x. In this study, the value of $\xi(x)$ is numerically generated by assuming a Gaussian auto-correlation function (ACF) which is characterized by a root-mean-square (rms) value of the fluctuation ε and a correlation distance a. In the inhomogeneous structure, we simulate 2-D scalar-wave propagation supposing crosswell geometry. We analyze the travel times of the simulated wavetraces with a standard tomography method to reconstruct velocity structures. As an example, two types of velocity structures are considered: both have the same large-scale inhomogeneity but have different small-scale inhomogeneities. The two reconstructed structures appear to be almost the same indicating that the travel-time tomography is insensitive to such small-scale inhomogeneities. To detect the small-scale inhomogeneity, we focus on residuals of the travel times; this study considers the difference between the travel times in $V_0(x)$ and $V(x)$ as residual. We investigate the statistical properties of the residual with changing the values of the small-scale inhomogeneity. The results show that the rms value of the travel-time residual increases with the value of ε. Furthermore, the residuals between adjacent stations correlate with each other, and its characteristic scale length strongly depends on the value of a. This implies a possibility of estimating the small-scale inhomogeneity from the ACF of the travel-time residuals. Based on the above results, we analyzed crosswell-tomography field data. We imaged large-scale inhomogeneity with a tomography method, and calculated the ACF of the travel-time residual. We found that the residuals of adjacent stations correlate with each other, and estimated the small-scale inhomogeneity by analyzing the ACF based on the simulation results in 2-D space. In future studies, 3-D wave-propagation simulations would be needed for more rigorous estimation.

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