論文の内容の要旨

論文題目　Study of high-frequency seismic wave propagation in heterogeneous structure inferred from dense array observations and numerical simulations

（不均質な地下構造を伝播する高周波数地震動の特性
—高密度地震波形記録解析と数値シミュレーションに基づく評価—）

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High-frequency seismic wave with frequency *f* > 1 Hz shows very complicated waveforms, such as distortion of the energy partitioning among three-component seismograms and developments of long duration *P*- and *S*-wave coda waves. Such complicated behaviors are considered to be caused by the structural heterogeneities, such as complex slip distribution, heterogeneities in subsurface velocity structure, irregular surface topography, and localized site amplification effect. Since waveform complication appears mostly in high-frequencies, it is considered that small-scale heterogeneities with scale comparable to the wavelength of seismic wave are its dominant causes. Such characteristics of complicated high-frequency seismic waves and their relation with heterogeneous structures have extensively been studied by many researchers based on theoretical and numerical approaches [e.g. Sato, 1984; Furumura and Kennett, 2005, 2008; Miyatake et al., 2008; Kumagai et al., 2011]. A detailed understanding of the characteristics of the high-frequency seismic waves is very important for revealing the physical properties of the source rupture process during the large earthquake and the propagation characteristics of high-frequency seismic waves in the Earth's interior. Moreover, it is equally important for understanding the cause of strong motion disasters for past earthquakes and for predicting strong motion disasters associated with future large earthquakes.

In this thesis, we examined in detail the features of the complicated high-frequency seismic waves associated with the scattering of high-frequency seismic waves due to heterogeneous velocity structure and irregular topography. We analyze a large number of seismograms recorded by dense seismic KiK-net, K-NET and Hi-net arrays of more than 1000 stations across Japan for several hundred earthquakes, in order to examine the change in the waveforms with increasing frequency and propagation distance.

Dramatic change in the high-frequency *P* and *S* waveforms with increasing propagating distance and frequency is confirmed by analyzing 1) the collapse of the apparent *S*-wave radiation pattern, and 2) the increase in the *P*- wave signal of the transverse component. Then, the physical process, that governs the propagation of high-frequency seismic waves through heterogeneous structures, is examined by 2-D and 3-D

FDM simulation of seismic wave propagation using heterogeneous structure model including irregular topography and stochastic random velocity fluctuation. Through the direct comparison of the observed characteristics from dense seismic array and the results of FDM simulation of seismic waves, the process of the disruption of high-frequency seismic waves during propagation in heterogeneous structures is clarified in detail.

In order to understand the complicated properties of high-frequency seismic wavefield and its dramatic change with increasing frequencies, we first examined the distortion of the apparent *S*-wave radiation pattern observed in dense seismic network. The observed waveforms from the dense KiK-net stations during the aftershock sequence of the 2000 Tottori-Ken Seibu earthquake demonstrated that the apparent *S*-wave radiation pattern observed during the strike-slip fault earthquakes is gradually distorted from a typical four-lobe shape to isotropic circular pattern as frequency increases over 1 Hz, and it shows almost isotropic circular pattern irrespective of the direction from the fault strike as frequencies approach to $f = 5$ Hz. Such collapsing of the apparent *S*-wave radiation pattern is also emphasized with increasing hypocentral distance and the effect is much stronger for high-frequency seismic waves. Therefore, it is expected that the major cause of such distortion in apparent radiation pattern is the scattering of high-frequency ($f > 1$ Hz) seismic waves due to small-scale heterogeneities along the wave propagation path, rather than due to other small-scale heterogeneities only near the source area or just below stations, such as caused by irregular source-rupture process and localized site amplification effect below station, respectively. In order to confirm this hypothesis, we conducted FDM simulation of seismic wave propagation using 2-D heterogeneous velocity structure model which is described by stochastic random velocity fluctuation. We employed a stochastic random velocity fluctuation model characterized by a von Karman power spectrum density function (PSDF) which has long been used to model small-scale heterogeneities in the lithosphere. The results of simulations clearly demonstrated (i) the effect of strong scattering of the high-frequency seismic waves due to heterogeneities with scale length comparable to or smaller than wavelength of seismic waves, and (ii) the distortion of the apparent *S*-wave radiation pattern during propagation through the heterogeneous structure. By comparing the results between the FDM simulations using a set of stochastic random velocity fluctuation models and observations, the velocity fluctuation for southwestern Japan upper crust model which is characterized by a von Karman-type PSDF with correlation distance of $a < 5$ km, fluctuation strength of $\varepsilon = 0.07$ and order $\kappa = 0.5$ can explain the observed features of the distortion of the apparent *S*-wave radiation pattern with increasing frequency and propagation distances.

Then, scattering strength of high-frequency wavefield is analyzed by examining relative strength of the *P*-wave energy of the transverse (T) component for the beginning part of seismograms, which is often used as an indicator of the strength of the seismic wave scattering in heterogeneous medium [e.g. Nishimura et al., 2002; Sato, 2006; 2007, Kubanza et al., 2007]. The results of this analysis showed that the PEP_T increases gradually with increasing frequency, but not with increasing travel distance. However, this value increases suddenly at larger hypocentral distances $D > 150$ km, where *Pn* phase propagating along the crust/mantle boundary (Moho discontinuity) is the dominant phase as the initial *P* waveform rather than the direct *P* wave. This may mean that the distribution properties of the small-scale velocity fluctuation in the upper, lower crust and upper mantle are completely different and causes different effects on the high-frequency seismic wavefield. Such difference in the distribution properties of the small-scale velocity fluctuation in the crust and upper mantle was confirmed by 3-D FDM simulation of seismic wave propagation using a layered structural model with different stochastic random velocity fluctuations. From the simulation results, we found much stronger fluctuation in velocity ($\varepsilon > 9$ %) and smaller correlation distance ($a < 5$km), associated with reflective lower crust and laminar sub-Moho structures, just below or above the Moho boundary, to explain data both from seismic reflection and dense array observation of earthquakes [e.g. Iwasaki et al., 2002; Iidaka et al., 2006]. We can roughly reproduce the observed properties of the high-frequency *P* wave propagation in heterogeneous structure by the FDM simulation with a velocity fluctuation model which was obtained by the analysis of the apparent *S*-wave radiation pattern. In addition, in order to reproduce the observed feature of the high-frequency wavefield more quantitatively, we should also employ another heterogeneous model such as explained by irregular surface topography and shallow low-velocity structure just beneath the station.

Another important cause of scattering of high-frequency seismic waves due to irregular surface topography is examined by 2-D and 3-D FDM simulation of seismic wave using the high-resolution structure model including irregular topography and comparing with that of ordinary flat surface model. The results of simulation clearly demonstrate how the complex irregular surface topography modify reflection pattern of the seismic waves. The results of simulation reproduce the observed feature of the complex coda envelope shape, increase in the *P*-wave amplitude of the transverse component and the distortion of the apparent *S*-wave radiation pattern as they propagate through the heterogeneous structure with realistic irregular surface topography. It is also found that the mean strength of seismic wave scattering due to topography can be explained by the power spectral density of the irregular topography for each area.

Such topographic scattering of the direct *P* and *S* waves has minor effect on the distortion of the high-frequency seismic waves compared with that due to velocity fluctuations as mentioned above, because the topographic scattering occurs only once below station and it is not accumulated during propagation of seismic waves for long distances. It is expecting that the strength of the velocity fluctuation and resulting seismic scattering energy may be overestimated more than 20 % if the effect of irregular topography is not taking into accounted in the simulation model.

The spatial distribution of the strength of the topographic scattering can be examined by calculating the PSD of topography for each region of Japan. Many researchers, including the results of present study, have claimed that there scattering of high-frequency seismic waves is strong in the back-arc side of northeastern Japan compared with the fore-arc side of northern Japan and other areas [e.g. Obara and Sato, 1995; Carcole and Sato; 2009]. According to the spectral analysis of the surface topography for each region, there is no clear difference in the PSD of larger wavenumber components among the back-arc side of northern Japan and other areas. Therefore, it is concluded that such a regional difference in the strength of scattering of high-frequency waves is mainly caused by local sub-surface structure i.e., different distribution property of small-scale velocity fluctuation in the crust and upper mantle. Strong scattering of high-frequency signals in the back-arc side of northeastern Japan can be explained by the heterogeneities characterized by 3-4% stronger fluctuation ε in velocity and smaller κ.

The results of waveform analysis for scattering high-frequency seismic waves were confirmed by FDM simulations of seismic wave propagation using the structure model including large-scale layered velocity structure, irregular surface topography and estimated velocity fluctuation model in each layer. It is confirmed that the observed seismic wavefield of relatively low-frequency ($f < 0.5$ Hz) signals are mostly controlled by large scale heterogeneities, which is often explained by a layered structure very effectively, but the propagation of the high-frequency ($f > 2$ Hz) wave field with shorter wavelength cannot be reproduced without including small-scale heterogeneities in each layer and realistic irregular surface topography Using this model, the feature of the observed high-frequency seismic wavefield, such as waveform shapes, energy decay, and distribution pattern of the *P* and *S* waves, can be well reproduced.

Through the improvements of the knowledge of high-frequency seismic wave propagation in actual heterogeneous structures and the developments of high-resolution simulation model including realistic surface topography and stochastic random velocity fluctuation, steadily increasing computer power and large-scale computational techniques will realize high-frequency seismic wave propagation simulation better in very near future.