論　文　内　容　要　旨

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学位論文の 題　　　目	Development in seismic interferometry for subsurface monitoring – an application to the 2011 Tohoku-oki earthquake – （地下構造モニタリングのための地震波干渉法の高度化 － 2011 年東北地方太平洋沖地震への適用 －）		

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概要

Seismic interferometry is a method to retrieve Green's function by cross-correlating passive wavefield such as ambient noise and coda wave. Green's function contains information of wave propagation. Thus, we can explore subsurface structure using the Green's function retrieved by seismic interferometry. An advantage of seismic interferometry is repeatability of Green's function retrieval. Meanwhile, subsurface monitoring is one of important issues in seismology. That is because the measurement of the temporal variation in subsurface structure will give us useful information about change in soil condition, crack density or aspect ratio, fluid distribution, and/or static stress. For reliable measurements of the temporal change in subsurface structure by seismic waves, the source of the seismic waves must be repeatable and/or stable. Therefore, seismic interferometry is a useful tool to monitor subsurface structure, giving repeatable and/or stable sources by cross-correlation functions of ambient noise or coda wave.

On 11 March 2011, the M9.0 Tohoku-Oki earthquake took place off NE Japan which various seismic observations cover. In order to deepen our understanding of the temporal change in subsurface structure related to the Tohoku-Oki earthquake, I deal with four subjects. The key words of the present study are three-component observation and array observation. I use two kinds of data: KiK-net and Tono array. Each KiK-net station has two of three-component accelerometers both on the surface and the bottom of borehole, configurating a vertical array. Tono array is a small-aperture, three-component, and broadband seismic array.

First, in Chapter 2, using the cross-correlation functions of coda wave observed at two horizontal components of KiK-net vertical array, I examine temporal change in shear velocity and polarization anisotropy related to the Tohoku-Oki earthquake. After the Tohoku-Oki earthquake, shear velocity within near surface layer decrease by up to 5-10% in the wide are in NE Japan. In contrast, the fast directions of polarization anisotropy do not show significant changes, which suggest that the static stress change due to coiseismic slip is not sufficient to change the orientations of cracks and/or the principle axes of crustal stress field. This study adds new information of the temporal change in subsurface structure related to the 2011 Tohoku-Oki earthquake.

Second, in Chapter 3, using the cross-correlation functions of ambient noise observed at vertical components of Tono array, I examine the frequency dependence of the coseismic velocity change related to the Tohoku-Oki earthquake in a wide frequency range of 0.3-1.9 Hz with a high frequency resolution of 0.18 Hz. Below 1.1 Hz, the coseismic phase velocity reduction linearly increases with respect to frequency, which is indicative of the near-surface velocity reduction. However, above 1.2 Hz, the phase velocity change shows more complicated behavior. Here, I develop a method to estimate the phase velocity and the noise source distribution simultaneously based on the spatial auto-correlation (SPAC) method. Based on the method, I show the suppression of the apparent velocity change due to the temporal change in the noise source distribution. This study shows that array observations of ambient noise have a potential to measure the temporal velocity change in a wide frequency band with a high frequency resolution and to suppress the effect of the change in noise source distribution by the simultaneous measurement of the phase velocity and the noise source distribution.

Third, in Chapter 4, using the cross terms of the cross-correlation tensor of ambient noise, I develop a novel method to separate body and Rayleigh waves. The method is based on a theoretical discovery that vertical-radial (ZR) and radial-vertical (RZ) components of the cross-correlation tensor have the opposite signs for elliptic Rayleigh wave and the same signs for rectilinear P wave. Accordingly, I separate P and Rayleigh waves by just taking sum and difference of ZR and RZ correlations. Furthermore, the application to Tono array data validates the effectiveness of the method. The method can be performed without any knowledge of velocity structure, using only two stations on the free surface, even in the case of anisotropic wave incidence, and with the quite simple procedure. This study proposes an effective use of three-component observation of ambient noise.

Fourth, in Chapter 5, using cross-correlation tensor of ambient noise observed at three components of Tono array, I reveal the composition of ambient noise. For estimating the composition ratio between Rayleigh, Love, and P waves, I extend the SPAC method to body wave incidence. The extended SPAC method shows a good

agreement between the theoretical and observed cross spectra. The obtained scomposition of ambient noise significantly changes at 1 Hz. While the P wave composition in total power is 5-15% and the lowest one below 1 Hz, the P wave composition suddenly increases above 1 Hz and reaches 50% and the highest one in those of three wave modes. The change at 1 Hz is attributed to the attenuation of high-frequency surface waves. This study demonstrates the effective use of the three-component array allowing us to decompose the ambient noise wavefield and to reveal the composition of ambient noise. The significant P wave above 1 Hz revealed in Chapter 5 is the cause of the complicated behavior of the phase velocity change in Chapter 3.

Seismic interferometry is a powerful tool for subsurface monitoring. However, we should take account of the effects of change in noise source distribution and the contamination of other wave modes to correctly interpret observed temporal variations in subsurface properties as shows in Chapter 3 and Chapter 5. Moreover, the present study shows that effective use of three-component array is a key for detecting change in not only seismic velocity but also anisotropy, for minimizing the effect of temporal change in noise source distribution, for measuring broadband velocity change with a high frequency resolution, for separating body and Rayleigh waves effectively, and for understanding the composition of ambient noise.

論文審査の結果の要旨

地震発生過程や地震に伴う諸現象の理解のためには，地下構造の時間変化を推定することが必要である．髙木涼太提出の博士論文では，地下構造の時間変化を推定するための手法の高度化ならびに 2011 年東北地方太平洋沖地震に伴う地下構造の時間変化の推定を行った。

まず， 防災科学技術研究所の強震観測網である KiK-net を用いて，地震に伴う S 波速度変化を検出した．KiK-net においては，地表と深さ数 m～数百 m の地中の二点に設置されている地震計間の地震波速度の時間変化の推定を行うことが可能である．その結果，地震に伴う S 波速度低下は東日本の広範囲で観測され，その大きさは 5-10%程度である。この原因は，強震動による地盤の弱化が考えられる．また，S 波偏向異方性の時空間変化の検出も行った．異方性の方向は水平圧縮応力軸の方向と一致する．異方性の方向に顕著な時間変化が無いことから，本震の断層すべりによる静的な応力変化は，異方性の原因となる地殻内の微小クラックの選択配向の分布を大きくは変化させてないと考えられる．

次に，時間的に連続して存在する常時微動を用いて，地下構造の時間変化の検出を行った．解析には，東北大学の岩手県遠野市における広帯域アレイ観測のデータを使用した．その際に常時微動源の時間変化を考慮し，年周変化の影響の軽減を試みた．その結果，0.3Hz から 1.1Hz の帯域において，0.1 から 0.5%の地震波速度低下を検出した．ただし，1.2Hz 以上の高周波数帯域においては異なる傾向が得られた．

そのため，アレイが三成分の観測で行われていることに着目し，各成分間での相互相関である，相互相関テンソルから，P 波とレイリー波を分離できることを理論的に示した．

この相互相関テンソル法を遠野広帯域アレイに適用した．その結果，約 1Hz を境に，高周波数側では，P 波が，低周波数側ではレイリー波が卓越することを示した．このことは，アレイ観測で得られた地震波速度変化の内、高周波数側は P 波の，低周波数側はレイリー波の速度の変化であると考えられる．低周波数側でのレイリー波の速度の低下の原因としては，強震動による地盤の弱化が考えられる．

以上の内容は，自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，髙木涼太提出の博士論文は，博士（理学）の学位論文として合格と認める。