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Seismic velocity changes associated with the 2011 Tohoku-Oki earthquake (Mw9.0) as inferred from analyses of direct and coda waves of repeating earthquakes

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論 文 内 容 要 旨

氏　　名	Jose Jesus Karim Pacheco Vivero	提出年	平成 26 年
学位論文の 題　　目	Seismic velocity changes associated with the 2011 Tohoku-Oki earthquake (Mw 9.0) as inferred from analyses of direct and coda waves of repeating earthquakes 繰り返し地震の直達波とコーダ波の解析により推定された 2011 年東北地方太平洋沖地震（Mw9.0）に伴う地震波速度変化		

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Abstract

Detecting seismic velocity changes in the solid earth has been of major interest and important to understand geophysical underground phenomena for many years. Since a pioneer work of Poupinet et al. (1984), seismic velocity changes have been measured with high resolution and reliability by using the waveforms excited from controlled artificial sources and natural repeating earthquakes that occur at same locations with the same mechanisms. Recently, seismic interferometry techniques using ambient noises or coda waves, which do not need same sources, are used to detect subtle medium changes. As a result, decreases of seismic wave velocity have been detected associated with the occurrences of large earthquakes at many fields. Examples are summarized in Chapter 1. The observed seismic wave velocity changes associated with the large earthquakes have been often considered to be caused by mechanisms such as near surface damage due to strong motions [e.g., Rubinstein & Beroza, 2005]. Also, stress changes in the medium have been inferred as a mechanism to generate seismic velocity changes in the subsurface and crust [e.g., Brenguier et al., 2008, Nishimura et al., 2005; Anggono et al., 2012]. There is a report on the velocity changes in the upper and lower crust during slow slip events that do not generate strong motions affecting the subsurface [Rivet et al., 2012]. However, the mechanism and depth extents of these seismic wave velocity changes are still matters under debate.

The 2011 Tohoku-Oki earthquake (Mw 9.0) provided us with an important opportunity to better understand seismic wave velocity changes occurring at shallow and deeper zones in the crust, because seismic waves are recorded by high-density seismic networks in a wide area of NE Japan that is subject to strong motions and large deformations. Several studies have already reported seismic wave velocity drops of up to 10 % in the subsurface due to strong motions after this earthquake from analyses of the records of the borehole and ground surface sensors [e.g. Nakata & Snieder, 2011; Takagi & Okada 2012]. Seismic wave velocity changes have been also inferred at

deeper zones down to 10 km from analyses of Rayleigh waves retrieved from ambient noises [Brenguier et al., 2014]. The enormous strain induced by the Tohoku-Oki earthquake might have introduced subtle changes in seismic wave velocity that extends deep in the crust beneath NE Japan. However, it is still unknown whether or not deeper crust has changed its seismic velocity associated with the Tohoku-Oki earthquake.

In the present study, we use direct body waves generated from repeating earthquakes. The analyses of repeating earthquakes have a merit in that the body-waves sample deeper zone between the sources and the receivers, which have not yet been analyzed for the case of the Tohoku-Oki earthquake. However, accurate measurement of changes in travel times of direct P- and S-waves is strongly dependent on the precision of the repeating earthquake locations, and because a large area of NE Japan was damaged, usual relocation methods of repeating earthquakes are not applicable. Therefore, we develop a new inversion method to detect subtle velocity changes in the medium as well as hypocenter parameters of repeating earthquakes. The new method is applied to the Hi-net data to reveal spatial distributions of the seismic velocity change in NE Japan. We further analyze the seismograms of repeating earthquakes recorded on the ground surface and at depths of about 100 m to understand the wave properties we analyzed. Finally, we discuss the structural changes associated with the Tohoku-Oki earthquake based on our results and previous studies that report the seismic velocity changes.

In Chapter 2, the new inversion method using arrival time differences of direct P and S-waves is described. The inversion method simultaneously determines hypocenter parameters and station correction factors of travel times of direct P- and S-waves. Since arrival time differences of body waves from a pair of repeating earthquakes occurring before and after the target large earthquake are represented as linear equations of relative locations and origin times of the two earthquakes and station correction factors that account for the velocity changes of medium, we are able to determine these parameters by using the least square method. We apply this method to a set of 25 repeating earthquakes located at depths between 30 and 60 km in NE Japan with magnitudes ranging from 3.4 to 4.7. Each pair of repeating earthquakes consists of two events occurring before and after the Tohoku-Oki earthquake. Direct wave arrival time differences are measured from seismograms recorded by 454 stations of Hi-net seismic network. Using a cross-spectrum method, we estimate arrival time differences up to about 0.01 s and 0.04 s for P- and S-waves, respectively. The results show that a wide area of NE Japan locating at 37-40° N in latitude, close to the large slip area of the Tohoku-Oki earthquake, indicates large station correction factors of about 0.005-0.04 s for S-wave. On the other hand, station correction factors for P-wave are much smaller. We examine temporal changes of the medium properties by dividing the 25 sets of repeating earthquakes in three groups and by analyzing a set of 15 repeating earthquakes that occurred only before the Tohoku-Oki earthquake. The results indicate no significant temporal change in the station correction factors. We further separately analyze the repeating earthquakes occurring in the north and the south regions of NE Japan, respectively. As a result, we observe significant spatial shifts of large station correction factors for S-wave: large station correction factors determined from the repeating earthquakes located in the north are shifted to the south area of NE Japan, while those from the repeating earthquakes in the south are shifted to the north area. This implies that the anomaly that decreased seismic velocity extends down to deep crust in the middle of the area where both large station correction factors are observed. We first determine the horizontal extent of the anomaly. We suppose that the horizontal extent of the anomaly is the region where station correction factors determined both from the north and south groups exceed a limit value (0.015 s). As a result, the anomaly is determined at the area extending N-S directions in the middle of NE Japan. We further estimate the depth of the anomaly to be at approximately 25 km from analyses of S-wave ray tracing in a layered spherical earth. The average velocity change is estimated to be about 0.1%. We examine the stability and accuracy of the inversion method by using a Jackknife test, and confirm that the hypocenters are located at approximately same regions independently of the set of repeating earthquakes. These results suggest that our inversion method properly determines the station correction factors and hypocenter parameters.

In Chapter 3, to examine the area where the seismic waves of repeating earthquakes propagate, we analyze triggered seismograms recorded at borehole and ground surface sensors of KiK-net. Comparison between the results obtained from the sensors installed at different depths allows us to infer the regions where the waves are sampling in the medium. We measure arrival time differences of body waves from the seismograms of 6 repeating earthquakes located at depths from 43 to 53 km in NE Japan with magnitudes ranging between 3.4 and 4.7. We correct the origin times of repeating earthquakes using hypocenter parameters determined in the previous chapter and estimate travel time differences of direct waves to be up to 0.01 s for P-waves and about 0.04 s for S-waves. From multi-lapse time window analyses of S-coda, velocity changes are estimated to be up to 0.2% at some stations located mainly at Iwate and Fukushima Prefectures in Tohoku region. These travel time differences and velocity changes measured at the borehole and ground surface sensors are very similar to each other. This suggests that the waves we analyzed sample the same region and not mainly consist of reverberations at subsurface but originate from deeper in the medium.

In Chapter 4, we examine the origins of the velocity changes detected in this study. We first compare the results of this study with peak ground accelerations and strains associated with the occurrence of Tohoku-Oki earthquake. The results show no clear correlation among them. The results are then compared and discussed with results reported in previous studies on the velocity changes associated with the Tohoku-Oki earthquake. Our results from analyses of KiK-net data indicate that the waves we analyzed do not consist mainly of the waves propagating or reverberating at depths of a few hundred meters. This is confirmed by a poor spatial distribution of seismic velocity changes by this study with the results of KiK-net data analyses by Takagi & Okada (2012). On the other hand, we find good spatial correlations with results of relatively long period (about 1-10 s) Rayleigh waves [Brenguier et al., 2014] and S-coda at 1-2 Hz [Nishimura et al., 2013]. The estimated velocity changes are also in the same amplitude ranges of about 0.1 %. To reconcile all these observations, we present a model of structural changes that explains the observations from this study and previous studies. The structural model consists of shallow layers (few hundred meters) with velocity changes up to 10 % and crust with velocity changes of about 0.1% that extends down to approximately 25 km beneath the middle of NE Japan, immediately west from the large slip area of the Tohoku-Oki earthquake. Although seismic wave velocity changes extending down to such depths in the lower crust are rarely reported, there is recently a reported example in which slow slip events generated a decrease of the seismic velocity in the crust beneath Mexico [Rivet et al., 2014].

In this study, we have succeeded in clarifying that seismic velocity changes associated with the Tohoku-Oki earthquake occurred not only at the subsurface but in the crust from our new inversion analyses of large number of arrival time data of repeating earthquakes. We found an anomaly of velocity change with about 0.1% extending down to approximately 25 km in the middle of NE Japan, close to the large slip area of the Tohoku-Oki earthquake. Considering the results from analyses of seismograms recorded at KiK-net stations and previous studies on the seismic velocity changes, we propose a structural model that consists velocity changes of up to 10% in subsurface (~100 m), and anomaly with an average velocity change of approximately 0.1% extending down to 25 km. This study has provided important evidence that seismic velocity changes associated with a megathrust earthquake are not limited to the shallow subsurface, but extend deeper in the crust.

論文審査の結果の要旨

固体地球内部構造の地震波速度変化は、相似地震等を利用した精度の高い解析方法が開発され、近年では雑微動を利用した地震波干渉法を用いて、世界各地で解析が行われるようになった。その結果、大地震の発生時には、強震動による表層地盤の剛性率低下に伴う地震波の速度減少が起きることが明らかとなった。一方、地球潮汐に伴う応力変化により地盤や浅部岩体の地震波速度が変化すること、また、大地震や火山噴火の発生時の周辺岩体の応力変化による速度変化についても少なからず報告がある。しかしながら、大地震の発生時には、解析対象となる地盤も強震動を受けるため、地盤やその下方にある地殻内部の応力による地震波速度については議論の分かれるところであった。

パチェコ・カリム君は、2011 年 3 月 11 日の東北地方太平洋沖地震を対象に、この課題について新しい解決方法を提示した。彼は、相似地震の相対震源決定と観測点補正値を同時に求める方法を開発し、東日本における Hi-net 地震観測網の数百点を超える良質のデータに新手法を適用した。データと得られた結果を丁寧に吟味した結果、地震時断層すべり量の大きかった領域の西側を中心とした、東北地方脊梁部の地殻上部から深さ 25km 程度の下部地殻まで地震波速度変化が生じたことを明らかにした。また、解析した地震波の波動特性を地表ー地中地震計のデータをもとに調べるとともに、地震波の伝播の特性を加味しながら、求められた結果と、先行研究により報告されている地盤浅部から上部地殻の地震波速度減少量とその空間分布との関係を明らかにした。

地殻深部における地震波速度の検出は、最近メキシコで１例報告されている。しかし、これは強震動を伴わないスロースリップの発生時に伴う速度変化であり、大地震に伴う地殻深部での地震波速度検出の事例はなかった。パチェコ・カリム君は、貴重な事例を新たに提供するだけでなく、今後、世界各地で発生する大地震に伴う地震波速度変化を系統的に調べる手法を提出した。これにより、地殻深部での地震波速度変化の有無、また、その生成要因のメカニズム解明につながると期待される。

以上から、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，パチェコ・カリム提出の博士論文は，博士（理学）の学位論文として合格と認める。