A study on early afterslip following the 2011 Tohoku-Oki earthquake deduced from onshore and offshore geodetic data

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論　文　内　容　要　旨

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氏　　名	MAULIDA Putra	提出年	令和 ３　年
学位論文の 題　　　目	陸域および海域測地観測から推定した 2011 年東北地方太平洋沖地震の初期余効すべりに関する研究 (A study on early afterslip following the 2011 Tohoku-Oki earthquake deduced from onshore and offshore geodetic data)		

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Abstract

The Tohoku-Oki earthquake (M_w 9.0) struck northeast Japan on March 11, 2011. A dense onshore geodetic network in tandem with seafloor geodetic observations captured large coseismic and postseismic deformation. Many studies have reported the afterslip distribution of this event. However, these previous studies mainly analyzed the distribution over an extended period, such as from a few dozen days to a few years. Only a handful of studies have investigated the early afterslip period of the 2011 Tohoku-Oki earthquake. Furthermore, those studies did not provide a sufficient understanding or rigorous discussion of the early afterslip area or aftershock activities. An understanding of the spatial and temporal evolution of the early afterslip, beginning immediately after such a massive interplate earthquake, is essential to understanding the frictional properties of the plate boundary. On this basis, I investigated the spatial and temporal evolution of the early afterslip following the 2011 Tohoku-Oki earthquake using on- and offshore geodetic data.

To identify the distribution of early afterslip, I utilized geodetic observations from onshore Global Navigation Satellite System (GNSS) and Ocean Bottom Pressure gauge (OBP) sites to quantify postseismic deformation during the 210 hours (approx. nine days) following the mainshock. I adopted the kinematic precise point positioning strategy and removed the sizeable coseismic displacement from the observed data associated with the large aftershocks. Next, I performed spatial filtering using common-mode error (CME) analysis. The CME analysis reduced the standard deviation of the onshore GNSS time series by 14% for the east-west component and 21% for the north-south component, mainly attributed to pillar tilting caused by thermal expansion via sunlight. The obtained time series was enhanced using principal component analysis (PCA), which reduced the signal unrelated to the postseismic deformation. Finally, I selected a combination of principal components (PCs) based on the normalized displacement field of each. Thus, the time series was reconstructed, and the cleaned time series showed an apparent trenchward postseismic deformation.

I removed the systematic effect of ocean tides, non-tidal oceanographic fluctuation, and sensor drift on the OBP time series. To estimate sea-floor deformation captured by the OBP sites, I fit the data with a logarithmic function based on decay time derived from the GNSS time series. Subsidence was captured at all the OBP sites, and the maximum displacement reached 18 cm.

I used the predicted postseismic deformation via viscoelastic relaxation from a previous study to assess this effect at the geodetic sites. The viscoelastic effect was relatively small compared to the observed data; 2% and 11% for the GNSS and OBP sites, respectively.

To estimate early afterslip distribution, I utilized L1-norm regularization, which is characterized by regularization without smoothing. I estimated the early afterslip distribution using data from GNSS and OBP sites looking at the cumulative static displacement and time dependence of the observation time series. To assess the reliability of this method for determining slip and the non-zero slip boundary, I performed a recovery test using both GNSS and OBP site data looking at assumed fault patches. The L1-norm inversion successfully recognized distinct regions of zero- and non-zero slip along the plate interface.

The main area of the estimated early afterslip was located off the shores of Iwate, Miyagi, Fukushima, and Ibaraki at a depth of 30–60 km. The slip was narrow along the dip direction with along-strike variation; the maximum slip

reached 5.8 m at northern Kinka Island. The estimated afterslip moment of release during those nine days was M_w 8.16. Several fault patches were estimated to occur offshore. These were estimated to explain the subsidence at the OBP sites, and they appeared to be located where the coseismic slip was relatively small compared to the surrounding area. Based on the kinematic afterslip results, I found that the afterslip-coseismic moment ratio of the Tohoku-Oki earthquake was relatively smaller than other large earthquakes. It may relate to the rupture of the 2011 Tohoku-Oki earthquake reaching from the down-dip to the up-dip of the potential region of the coseismic slip.

The spatial extent of the afterslip was related to frictional properties, therefore I examined the decay time of the early afterslip time series in each fault patch. The decay time result shows the along strike variation. In Off Miyagi and Iwate, the decay time tend to be shorter compared to the Fukushima region. The shorter decay time may reflect a small amount of normal stress on the plate interface and/or a small “*a-b*” or larger *k* value. Considering (*a-b*)~0, it may reflect that the early afterslip region corresponds to the transition from velocity weakening to the velocity strengthening.

I examined the spatial relationship between the early afterslip with the down-dip limit of the interplate earthquakes and the distribution of the aftershocks. First, the estimated early afterslip distribution was consistent with the down-dip limit of the interplate earthquakes off Miyagi and Iwate. Several cross-sections along the strike direction clearly showed the different characteristics and locations of the afterslip and aftershock activities. For example, off Miyagi and Iwate, the location of afterslip tended to be in the up-dip portion of the larger afterslip area. In contrast, off Fukushima, the distribution of aftershocks was in the down-dip of the larger afterslip area. This discrepancy is attributed to along arc-variation with different structural characteristics between off Miyagi and Fukushima region.

Based on the temporal evolution of afterslip, I emphasized the relationship between early afterslip evolution and the number of aftershocks. Aftershock–afterslip temporal evolution is consistent in almost every region, although the regions off Iwate and Miyagi showed a lack of aftershocks 30 hours after the mainshock, in contrast with the estimated early afterslip. Meanwhile, I found different characteristic in Fukushima and Ibaraki, where there is abundant number of aftershocks occurred more than afterslip. Such a discrepancy shows the factors other than afterslip were contributing to triggering aftershocks.

The spatial and temporal evolution of seismic and aseismic slip is related to the properties of the plate interface. Therefore, estimating the distribution of each slip behavior will be necessary to study earthquake hazard.

別　紙

論文審査の結果の要旨

本論文は，2011 年 3 月 11 日に発生した東北地方太平洋沖地震（2011 年東北沖地震）直後の初期余効すべりを海陸の測地観測データから推定，議論したものである。地震直後の余効すべりの時空間的様態を把握することは，断層面上のすべり収支および摩擦特性を把握する上で重要である。一方，地震発生直後から数日間の時間帯域における余効すべり現象を扱った先行研究は，それら時間帯域における全地球測位システム(GNSS)による変位時系列のノイズレベルが高いために事例が少ない。これら背景より本論文では(1) 2011 年東北沖地震の余効変動の様態を海陸の測地データから明らかにすること，(2)それら測地データから初期余効すべりの時空間的な特徴を明らかにすること，(3) 推定された初期余効すべりの深部下限およびプレート境界における摩擦特性の特性について議論すること，(4) 余震活動と初期余効すべりの空間的特徴について明らかにすること，以上 4 点をその研究目的とした。

(1)について，GNSS データをキネマティック精密単独測位方式で解析した後に，共通誤差成分解析および主成分分析を適用し，ノイズレベルを大きく低減した。併せて海底水圧計(OBP)データについてもノイズ低減処理を行い，海陸の余効変動場をきわめて高い精度で得た。

(2)について，初期余効すべりの空間的特徴を把握するために L1 正則化を用いた推定を行った。その結果初期余効すべりは主として地震時すべりの深部延長に帯状に位置することを明らかにした。

(3)について，推定された初期余効すべりの深部下限と低角逆断層型地震の発生下限が，宮城および岩手県南部ではよく一致する一方で，福島県南部および岩手県南部では両者が一致しないことを明らかにした。

(4)について，初期余効すべりと余震活動との比較を行い，岩手県南部および宮城県では，初期余効すべりの浅部延長上に余震が集中するのに対し，福島県南部では初期余効すべりの深部延長に余震活動が集中するという特徴を明らかにした。これらはプレート境界における摩擦特性の差異を反映している可能性がある。

これらの内容は，Maulida Putra 氏が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す。以上より，Maulida Putra 氏提出の博士論文を，博士（理学）の学位論文として合格と認める。