Significance of Stress Interactions Related to the Occurrence of Shallow Slow Earthquakes

（浅部スロー地震の発生に関連した応力変化とその相互作用）

Satoshi Katakami

1. General Introduction

Various earthquake phenomena with longer rupture durations than those of regular earthquakes, or “slow” earthquakes have been studied using high-density seismological and geodetic observation networks on land [e.g. *Obara and Kato*, 2016]. Some slow earthquakes preceded the occurrence of large earthquakes, such as the 2011 Tohoku-Oki earthquake [e.g. *Ito et al*., 2013] and the 2014 Iquique earthquake [e.g. *Ruiz et al*., 2014]. It is important to reveal the interaction of occurrence between slow and large megathrust earthquake because especially the Japan Meteorological Agency (Cabinet Office, Japan) issues warning of occurring quite large earthquake after occurring irregular slow slip event estimated rupture region of Nankai Mega-earthquake immediately. Slow earthquakes were triggered by the other stress perturbations, such as tidal change, static and dynamic stress change from the other earthquakes [e.g. *Miyazawa & Mori*, 2005; *Miyazawa & Brodsky*, 2008; *Ide et al*., 2010; *Itaba & Ando*, 2011; *Zigone et al.*, 2012; *Walter et al*., 2013; *To et al.*, 2015; *Houston et al*., 2015; *Araki et al.*, 2017; *Wallace et al.*, 2017]. Therefore, in this thesis, we focus stress sensitivity of shallow slow earthquakes, (tidal response for tectonic tremor and effect of perturbation of seismic wave for slow slip), which might be a pre-event of the megathrust earthquake, may contribute to identify the “pre-pre-event” of the megathrust earthquake.

2. Interactions between slow earthquakes and megathrust earthquake (Tohoku-Oki earthquake)

We identify the spatio-temporal variation of tectonic tremor activity before Tohoku-Oki earthquake to reveal the interactions between slow and fast slip. We applied a modified frequency scanning method [e.g. *Sit et al*., 2012; *Katakami et al*., 2017; 2018] to detect low-frequency tremors with ambient noise and identify their sources using data recorded by single ocean bottom seismometers (OBSs). By analyzing records from 17 OBSs deployed off the Miyagi Prefecture coast, an area that featured major coseismic slips during the 2011 Tohoku-Oki earthquakes [e.g. *Hino et al*., 2000], we investigated tectonic tremor activity patterns in the shallow part of the subduction zone from 1 December 2010 to 9 March 2011, immediately before the occurrence of the largest (Mw = 7.3) foreshock. Calculating the ratios of the envelope waveforms in the three different frequency bands at a single station, we estimated approximate tectonic tremor source areas according to the spatial distributions of the OBS sites that detected the tectonic tremors, as well as the spatiotemporal variations of tremor location and energy in the Tohoku-Oki earthquake coseismic slip area. We detected more than five multi-day tectonic tremor event clusters, some of them accompanied by an SSE, beginning approximately 1 month before the largest foreshock of the Tohoku-Oki earthquake. The tectonic tremor activity in late January and early March was detected at stations located near the Japan Trench (~35 km from the trench axis). which locate around updip end of SSE fault. Between these two terms, the three tectonic tremor clusters in February was located ~50 km from the trench axis and the observation distribution roughly corresponded to the fault area of the SSE. The source was consistent with the region of a relatively small number of regular earthquakes. At the updip end of the seismogenic zone on the plate boundary, effective stress is expected to be low due to low normal stress, making tectonic tremors frequent and small in amplitude, similar to those on the downdip end.

3. Tidal responses for shallow tectonic tremors

We reveal the tidal response in shallow tectonic tremor in Nankai Trough because there are no observations about it in Japan to clear the stress interaction for shallow slow earthquakes. Based on the modified frequency scanning method at a single OBS in southwestern Kyushu from 20 April to 3 July 2013, we successfully detected many tremor events including tectonic tremors with small amplitude that had not been detected in previous work based on multiple station analysis, such as the envelope correlation method which was reported by *Yamashita et al*. [2015]. We also evaluated the tidal response of the tremor activity with calculated the sea surface change using a computational model and statistically evaluated the relationship between tremor occurrence time and tidal phases based on the Schuster p test [e.g. *Tsuruoka et al*., 1995; *Tanaka et al*., 2002]. In the early stage of the tremor activity, tremors are mostly modulated by slow slip events. In contrast, we found a seismic response to ocean tides during the later stage in the shallower part of the subduction zone. This might indicate that the tremors are triggered by tidal changes caused by fault weakening due to slow slip events as same as deeper condition.

4. Stress sensitivity of instantaneous dynamic triggering of shallow slow slip events

We describe the stress interaction to shallow slow slip events as well as shallow tectonic tremors, in order to assess the stress conditions to trigger shallow slow slip events, which are recognized with seafloor borehole pressure gauges off Kii Peninsula [*Araki et al*., 2017]. We examined stress sensitivity of dynamic triggering of shallow SSEs in the Nankai Trough subduction zone offshore of Kii Peninsula, Japan. Using two borehole pore pressure data in DONET network, existing VLFE catalogue [e.g. *Takemura et al*., 2019] and newly identified tectonic tremors to analyze OBSs in DONET network, we inferred additional shallow SSEs that have not been reported in previous studies and obtained a 15-year long catalogue of shallow SSEs offshore of Kii Peninsula. We then estimated dynamic and static stress perturbations on the Philippine Sea plate interface induced by 18 candidate regional earthquakes using three-dimensional finite difference method simulations of seismic wave propagation (OpenSWPC; *Maeda et al*., 2017). We found that shallow SSE propensity to dynamic triggering depends mainly on the maximum Coulomb stress perturbation and that relatively large dynamic perturbations (>10–20 kPa) are needed to trigger a shallow SSE in the Nankai Trough. Regional earthquakes that can induce such large amplitude of dynamic stresses on the plate interface are relatively rare, which might explain the scarcity of dynamic triggering of large, detectable SSEs along the Nankai as well as other subduction zones. In addition, our analysis indicates that the timing of the perturbation with respect to the SSE cycle may affect the SSE propensity to dynamic triggering in the Nankai Trough. Furthermore, intra-slab earthquakes may efficiently trigger SSEs in subduction zones via less-attenuated, slab-guided waves. Comparison of estimated dynamic stresses with and without a low-velocity wedge supports the idea that an accretionary wedge in subduction zones promotes the dynamic triggering of shallow SSEs.

5. Does the magnitude of stress sensitivity control the magnitude of triggered events?

We discuss the relationship of magnitude between stress perturbation of causal event and the triggered events. Quite large stress perturbation from the Tohoku-Oki (> 100kPa), Mie-ken Nanto-Oki (> 40kPa) and Kumamoto (> 20kPa) earthquake triggered a large magnitude shallow SSE (2-4 cm slip; *Araki et al.*, 2017) compared to spontaneously occurring SSEs (1-2 cm slip; *Araki et al.*, 2017). Small stress perturbations from the tides on the plate boundary (a few kilo pascals) also trigger shallow tectonic tremors (less than Mw 2.0). These results could represent that the magnitude of the triggered slow earthquake is correlated with the amount of the change of stress that accompanies the causal event. Furthermore, it may be possible that increasing external stress contributes to increasing the magnitude of triggered slow earthquakes. The magnitude of triggered VLFEs might be larger than those of the background VLF events [*Miyazawa*, 2019], which is also seen in the relationship between triggered and background LFEs [e.g. *Miyazawa*, 2012]. How about for SSEs? Here, we try to compare between the moment magnitude of a triggered slow earthquake and the maximum coulomb stress on the plate boundary from the causal event.

Here, we summarize the magnitude of the other triggered slow earthquake which have not been mentioned in this study to take into account the results from previous studies (Table 1 & Figure 1). The number of observations for which a large magnitude event (Mw>5.0) was triggered with a small stress perturbation (< 10 kPa) is only two (Figure 1), while there are 6 examples of large magnitude events (Mw > 5.0) triggered with large stress perturbations (> 10 kPa). Relatively small dynamic stress perturbations with a maximum stress of less than < 10kPa trigger only a few large magnitude slow earthquakes (> Mw5.0). On the other hand, there are many SSEs (especially, shallow SSEs) triggered by large stress perturbations greater than 10kPa. However there are many observations for which a small magnitude event (Mw < 5.0) was triggered with a small stress perturbation (< 10 kPa). This observation could indicate that increasing the external stress contributes to increasing the magnitude of triggered slow earthquakes. However, what is the mechanism?

This observation could represent the increasing external stress contribute to increase the magnitude of triggered slow earthquakes. An injection of fluid could be one of possible mechanism to increase the fault slip area and/or the amount of slip. Some geophysical surveys, numerical models, and laboratory studies using core materials from science ocean drilling projects focused on the near-trench region suggest that shallow slow earthquakes occur in areas of highly over-pressured fluid and low effective stress conditions, as well as within fault rocks characterized by transitional frictional behavior

[*Saffer and Wallace*, 2016]. Therefore, deformation accompanied with dynamic stress perturbation could open a crack, and enhance injecting and moving of fluid to new crack. The deformation of crack opening lead to increase the area around slip-able fault with high pore-fluid pressure, and consequently redistribute pore-fluid pressure.

Table 1. List of moment magnitude of triggered events and maximum coulomb stress change of causal event

Triggered Event	Mw of triggered event	Mw err.	Maximum ΔCFF	ΔCFF Err.	Friction Cofficient	Causal Event	Refference
Shallow SSE in Nankai	5.50	0.30	338.48	77.13	0.1	2011 Mw9.0 Tohoku-Oki earthquake	This thesis & Araki et al. (2017)
Shallow SSE in Nankai	5.30	0.30	0.64	0.12	0.1	2014 Mw6.3 Iyo-nada earthquake	This thesis & Araki et al. (2017)
Shallow SSE in Nankai	5.50	0.30	44.32	25.47	0.1	2016 Mw6.0 Mie-ken Nanto-Oki earthquake	This thesis & Araki et al. (2017)
Shallow SSE in Nankai	5.50	0.30	20.67	5.29	0.1	2016 Mw7.0 Kumamoto earthquake	This thesis & Araki et al. (2017)
Shallow SSE in Hikurangi	7.10	0.50	350.00	250.00	0.6	2016 Mw7.8 Kaikoura earthquake	Wallace et al. (2017)
Shallow tectonic tremor in Nankai	1.74	0.21	6.00	2.00	0.6	Tidal changes	This thesis
Shallow VLFE in Nankai	4.00	0.60	5.00	3.00	0.08	Tidal changes	Nakamura et al. (2015)
Shallow VLFE in Nankai	3.85	0.45	0.95	0.55	0.4	2016 Mw6.0 Mie-ken Nanto-Oki earthquake	Miyazawa (2019)
Deep tectonic tremor and SSE in Guerrero	6.60	0.00	116.00	0.00	0.4	2011 Mw9.0 Tohoku-Oki earthquake	Hirose et al. (2012)
Deep tectonic tremor and SSE in Nankai	5.30	0.00	0.60	0.00	0.6	2009 Mw7.6 Tonga earthquake	Itaba & Ando (2012)
Deep tectonic tremor	1.00	1.00	5.00	4.00	~0.5	Tidal changes	e.g. Miyazawa and Brodsky (2008), Natata et al. (2008) & Thomas (2009)
Deep VLFE in Nankai	3.85	0.45	0.95	0.55	0.4	2016 Mw6.0 Mie-ken Nanto-Oki earthquake	Miyazawa (2019)

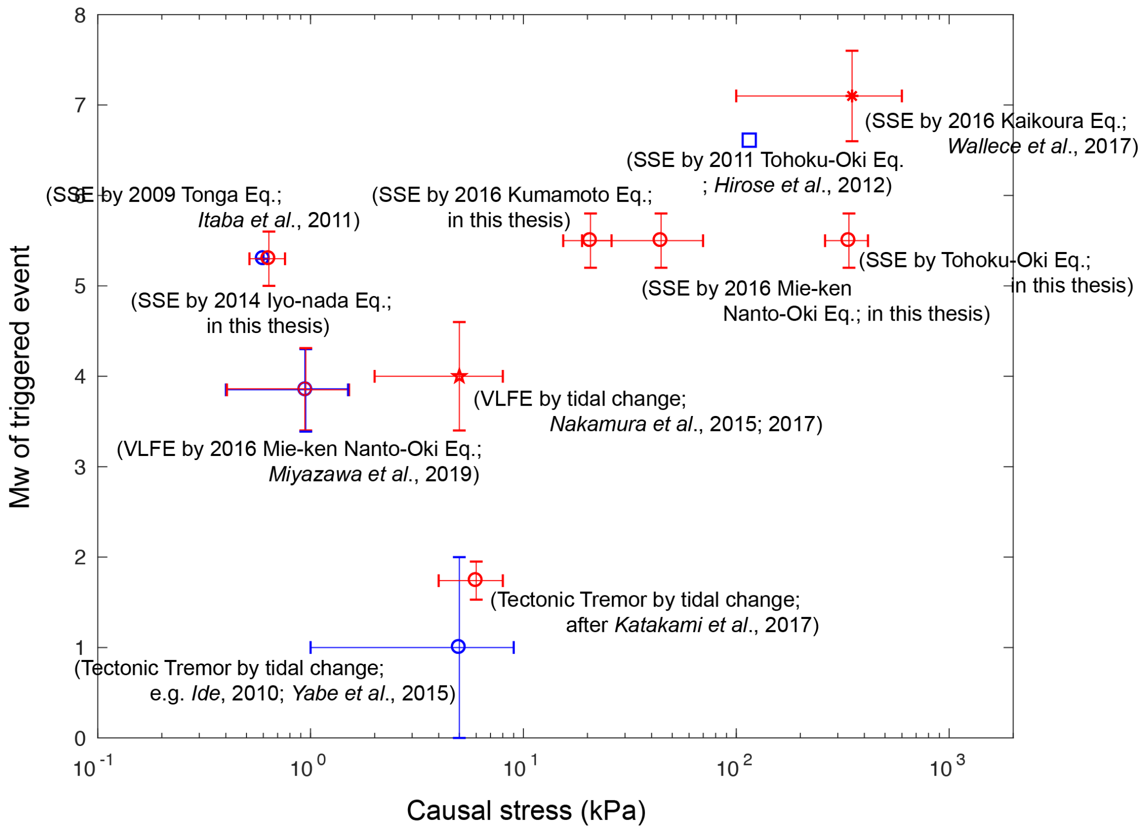

Figure 1. Stress perturbation of causal event versus the moment magnitude of triggered events for slow earthquake in both shallow (red) and deep (blue) subduction zone. Slow earthquakes occurred in Nankai (circle), Tohoku (square), Ryukyu (star) and Hikurangi subduction zone (asterisk).