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ORIGINAL ARTICLE

Synchronous Tremor Modulation During the Passage of 2012 Super-typhoon Jelawat in Nankai Trough: By Chance or Real Consequence?

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ABSTRACT

Episodic tremor and slow-slip events are sensitive to the exogenous stress perturbations process. Although tidal and remote triggering phenomena of tremors are well-established facts; however, the triggering mechanism induced by low-barometric pressure of typhoons or larger storms remains poorly addressed. In this paper, a time-synchronous tremor modulation is presented from the northern Kii Peninsula in western Japan, associated with a large Super Typhoon Jelawat, which occurred on September 30, 2012. It has been argued that such tremor excitation may not be correlated with other types of signal, such as the short-term or long-term slow-slip events, tidal effect, or remote triggering. The atmospheric low-pressure condition during the passage of super typhoon Jelawat causes vertical crustal uplift by a negative load and hence possibly enhances the thrust motion due to unclamping effects on the fault. Therefore, it is suggested that the synchronous tremor modulation process in the northern Kii Peninsula is a real consequence induced by super typhoon Jelawat.

INTRODUCTION

With the global expansion and enrichment of geodetic, geological, and seismological constraints in the past two decades, episodic tremor and associated slow-slip or episodic tremor and slip (ETS) events, hosted in brittle-ductile fault transition zones, have become a focal point of scientific exploration (Bürgmann, 2018). It has been proposed that slow-slip events may act as a possible stress-meter for great earthquake cycles, capturing time-dependent stress accumulation on adjacent locked segments of subduction megathrusts (Obara and Kato, 2016). Since there first discovery in western Japan (Obara, 2002); now it has been reported in diverse tectonic regions worldwide, e.g., northern Japan, Cascadia, Mexico, Costa Rica, New Zealand, Alaska, Hawaii, Basin-and-Range province, Central Himalaya, Sumatra, the Atacama Desert in Chile, San Andreas fault, among others (Bürgmann, 2018; Panda et al., 2018, 2020; Obara and Kato, 2016; Jolivet and Frank, 2020). Among all identified locations, the Nankai subduction zone in western Japan (Obara et al., 2004) and the Cascadia subduction zone in the Pacific Northwest of North America (Wech and Creager, 2011) are probably the best instrumentally monitored regions for tremor and ETS, with the availability of mature geodetic/seismological datasets.

It has been argued that tremor and ETS events are extremely sensitive to exogenous stress perturbations because of inherent fault weakness. Further, characterization of critically stressed seismogenic faults can be used as a proxy to probe into stress/frictional condition of faults, along with its sensitivity for tremor modulation by exogenous stress perturbation. A large tremor episode has been found to trigger small earthquakes (Vidale et al., 2011). Sometimes, tremor activity itself shows transient modulation in response to earth tides (Thomas et al., 2012; Thomas et al., 2009), the passage of seismic waves from remote earthquakes (Gomberg, 2010; Shelly et al., 2011; Kundu et al., 2016) and even by adjacent ETS events (Obara and Kato, 2016). In fact, a number of strain transient events, primarily coincident with low-barometric pressure during passages of typhoons, were also reported from Taiwan (Liu et al., 2009; Hsu et al., 2015).

Although the tidal and remote triggering of tremor and ETS are well-established phenomena, however, triggering potential induced by low-barometric pressure during passages of typhoons and tremor modulation/triggering mechanism remains equivocal. In this paper, a time-synchronous tremor modulation process is reported from the northern Kii Peninsula region of the Nankai trough in western Japan, with a large super Typhoon Jelawat that has struck the Kii Peninsula on September 30, 2012 (Fig.1). Further, it is discussed that the present observation of the synchronous tremor excitation process in the northern Kii Peninsula is a real consequence, or it may be just a coincident occurrence.

SUPER TYPHOON JELAWAT AND SYNCHRONOUS TREMOR MODULATION IN NANKAI TROUGH

The typhoon Jelawat formed in the Philippine Sea on September 20, 2012, has reached "super typhoon" status by September 24, with maximum sustained winds above ~240 km/hr, passed through Okinawa Prefecture on September 29, and finally made landfall over the Aichi Prefecture in southwest Japan on September 30. From the spatio-temporal migration path of super typhoon Jelawat (i.e., September 20 to October 1, 2012) in Fig.1, it is appeared that at 06:00-10:00 UTC on September 30, the eye of this super typhoon has approached very close to tremor patches in the Kii Peninsula along Nankai trough. Specifically, here the tremors occur in a narrow belt-like zone from Honshu to western Shikoku at ~30 km depth on the subducting interface of the Philippine Sea plate below southwest Japan Islands (Fig.1). Moreover, these tremors have been considered as a shear slip on the subducted plate contact surface, characterized by small clusters

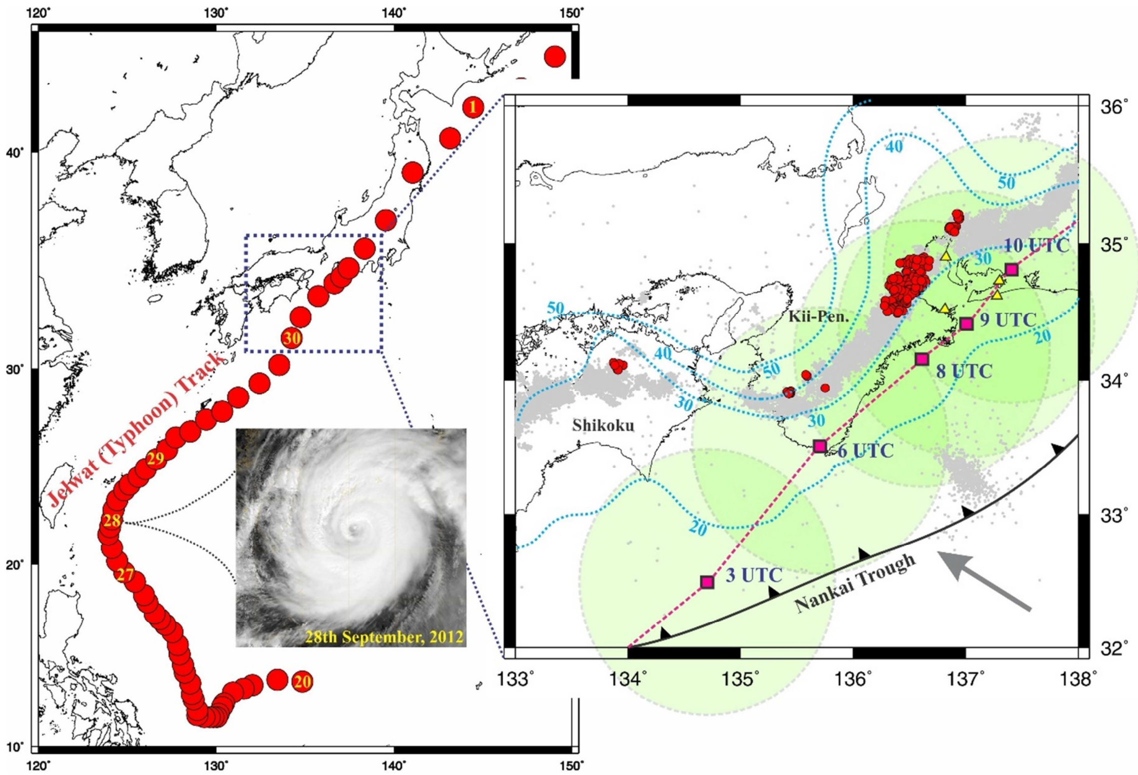

Fig.1. Spatio-temporal migration path of Super Typhoon Jelawat (20th September to 1st October, 2012) taken from Japan Meteorological Agency (JMA), RSMC Tokyo-Typhoon Centre. NASA's Terra satellite passed over Super Typhoon Jelawat on September 28 and the Moderate Resolution Imaging Spectroradiometer captured an infrared image as the storm approaches Okinawa, Japan (http://www.nasa.gov). Zoomed Panel: Locations of tectonic tremors in western Japan shown as grey [archived from the World Tremor database, http://www-solid.eps.s.u-tokyo.ac.jp/~idehara/wtd0/Welcome.html] and red dots represent short period tremor swarm from 29th September to 1st October, 2012. Pink squares and associated green circles representing the eye position of the Super Typhoon Jelawat (during 30th September at a different UTC) and the radius of the major storm axis (from Japan Meteorological Agency) respectively. Iso-depth contours of the Philippine Sea plate (Ide et al., 2010) are shown with 10 km intervals. Yellow triangles are the stations used for tidal height measurements (Japan Meteorological Agency). Vectors represent the slip direction of the Philippine Sea plate relative to the overlying plate.

and tremors that occur episodically with certain recurrence intervals (Ide et al., 2007; Ide and Tanaka, 2014).

Interestingly, a clear time-synchronous tremor modulation has been observed in the northern Kii Peninsula, along with the narrow belt-like tremor patches, when the eye of the super typhoon Jelawat approaches closest (~100-200 km) to the epicenter of the tremors patches (Fig.2). Moreover, from 20-28 September, well before approaching super typhoon in the Nankai trough region, we do not notice any tremor activity at all. However, it has started on 29 September, reaching its highest frequency during 30 September with the occurrence of significantly longer duration tremor activities (>100 seconds duration) and tremor activity persists for the next 4-5 days (Fig.2). Such time-synchronous tremor modulation also has been captured in the cumulative plots of tremor number, and we have noticed a clear step-like increase in tremor frequency during the storm surge period. It is suggested that such time-synchronous tremor modulation with the super typhoon Jelawat in the Kii Peninsula is due to change atmospheric pressure and subsequent enhance in thrust motion due to unclamping on the plate contact surface. Here, a possible connection between the change in atmospheric pressure and fault slip is made and a rough estimate of the stress changes on the plate contact surface is presented, assuming an elastic medium approximation. A pressure drop of Δp (~50 hPa) reduces the respective vertical stress; however, the horizontal stress due to plate convergence remains unchanged as the low-barometric pressure occurs over larger domains during passages of super typhoons, as its radius of influence is significantly large (Fig.2). Under such simple approximation, this significant drop in atmospheric pressure promotes failure on the plate contact surface by unclamping $\Delta p.Cos\ (\theta_{dip}) \approx 4.7\ kPa$,, lowering in normal stress, where θ_{dip} - dip of the plate contact surface is considered as 20°, and by enhancing the reverse shear stress $\Delta p.Sin\ (\theta_{dip}) \approx 1.7\ kPa$. It has been argued that this rough estimate of stress change due to low-barometric pressure is significantly above the critical triggering threshold (Peng et al., 2009; Gomberg, 2010; Thomas et al., 2009; Ziv and Rubin 2000).

JUST A COINCIDENCE OR A REAL CONSEQUENCE?

However, it can be argued because tremor occurs all the time, and they may correlate with other types of signal, such as the short-term or long-term slow-slip events or tidal effect. Hence, several potential questions have been raised regarding the typhoon triggering of tectonic tremors to address further. Tremors with a short duration, like the present case of an investigation, are often modulated (or triggered) by tidal stress oscillation, and this feature appears a common characteristic of tremors reported worldwide (Ide, 2012; Thomas et al., 2013; Thomas et al., 2009). Using tidal height measurements of the Japan Meteorological Agency (JMA) from the Kii Peninsula region, tidal normal/shear stress changes is computed (~0.5 kPa and 0.1 kPa) on a fault plane dipping ~20° and have presented a linear lag-correlation between tidal stress with tremor frequency (Fig.2b). No significant correlation between them is found (Fig.2b). It is argued that synchronous tremor modulation in the northern Kii Peninsula occurs during the intra-ETS period; hence, it has not been correlated with the slow-slip events. Further, the possibility of remote triggering phenomena has been discarded, as there was no report of the occurrence

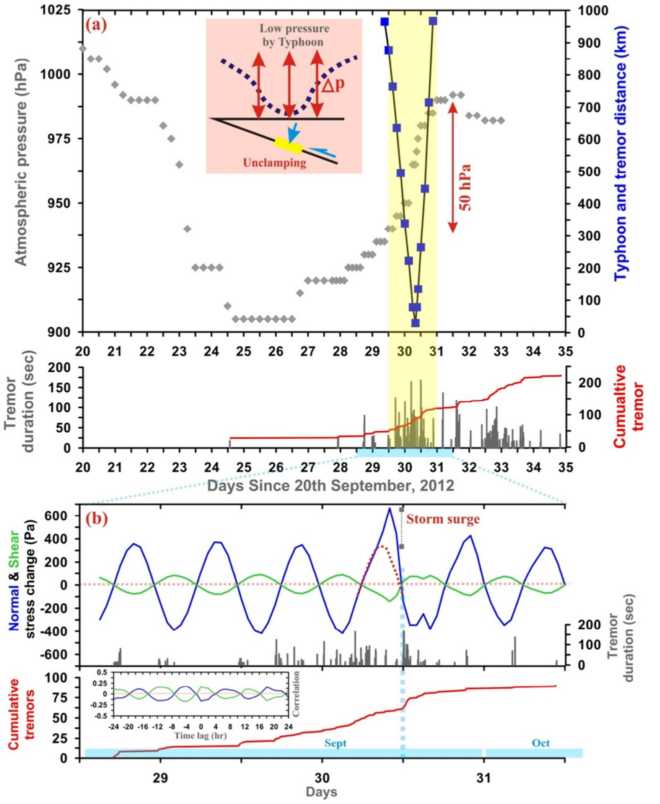

Fig. 2. (a) Temporal variation in Atmospheric pressure, Tremor duration (by grey spikes), Cumulative No of tremor activity (by red curve), and distance between epicenter position of the Super Typhoon Jelawat and tremor location (by blue squares). **(b)** Tremor time series with superimposed with tidal induced stresses (Shear and Normal) and Cumulative No of tremor activity. Effect of tidal load-induced stress variations has computed on the subducted Philippine Sea plate (at 30 km depth with dip angle as 20°). Note tidal load-induced shear (green; positive favours thrust slip) and normal stress changes (blue, positive indicates fault compression and negative indicates unclamping). Note clear evidence of Storm surge during Super Typhoon Jelawat passed over the Nankai trough. Also, note there no prominent cross-correlation between rates of tremor activity (per hr) with tidal-induced shear/normal stress oscillation (inset small panel).

of strong earthquakes in the surrounding region of the tremor patch. Moreover, Obara and Hirose (2006) also reported sharp coherent pulses in tilt data appeared on August 19-22, 2001, August 8-9, 2003, and January 12-13, 2004, respectively, from the northern Kii Peninsula, that have correlated to the typhoons and large storms with low atmospheric pressure. The step-like tilt changes in all three previous cases are coincident with the major tremor activities (Obara and Hirose, 2006). Therefore, the northern Kii Peninsula is susceptible to a low atmospheric pressure-induced tremor modulation process. The presence of anomalous pore fluid pressure along the tremor patches in the northern Kii Peninsula brings the inter-plate segment into the conditionally stable frictional domain and makes it more sensitive to typhoon/large storm-induced stress perturbation by low atmospheric pressure (Kodiara et al., 2004).

HYPOTHESIS FOR TYPHOON TRIGGERING/ MODULATION AND FUTURE DIRECTION

Hence, in view of all the arguments, the present observation of the synchronous tremor modulation process in the northern Kii Peninsula during the passage of a large super typhoon Jelawat 2012 appeared to be a real consequence indeed. Moreover, the effects of low atmospheric pressure, accumulation of rainwater, and inflation of soil due to increasing pore water pressure during the super cyclone may be recorded as rhythmic changes in altitude by the GNSS receivers. However, there are no clear signatures of ground subsidence captured trough the vertical GPS time series along the landfall region, which may possibly due to lower temporal resolution of the GPS data. However, the generation of tremors depends on the flexural response of elastic crust due to the above-mentioned variations. In such cases, flexing of the crust may be possible when the elastic thickness of the lithosphere is extremely low. In a stable continent, the underlying rock-fracture systems always maintain equilibrium with respect to the surrounding stress field. Activation of any fault needs disturbance of equilibrium and activation of differential stress-causing fault movement. Therefore, the pressure variation during a super cyclone may not always cause the reactivation of fracture system generation of the non-tectonic tremors.

Recently, Zhan et al. (2021) has presented three possible stages of vertical crustal movements associated with the typhoon passage. It is suggested that such typhoon-induced vertical crustal movements also influence the fault stability and tremor modulation process (Fig.3). In the first phase, the atmospheric low-pressure system causes vertical crustal uplift by a negative load and hence enhances thrust motion due to unclamping effects on the fault. In the next phase, heavy rainfall events after landfall of a typhoon depress the ground as a positive load and hence suppress thrust motion due to clamping on the fault. Finally, in the last phase, during clear conditions immediately after the occurrence of a low-pressure system, surface water drained to the ocean, groundwater causes poroelastic rebound/uplift and hence promotes thrust motion again due to unclamping process. It is acknowledged that the degree of vertical uplift due to increasing pore water pressure is directly proportional to the thickness of soil over the crust (Zhan et al., 2021). Therefore, the effect of increased pore pressure and associated surface uplift and reactivation of fault may not be much effective in the present case.

From this, one should expect synchronous tremor modulation/ triggering during the first phase of vertical crustal uplift by a negative load, whereas tremor modulation/triggering with time lag can be expected during the final stage of poroelastic rebound/uplift (Fig.3). However, it is difficult to separate all three phases and their influence separately during the tremor modulation/triggering or suppressing the process.

Therefore, in the future, the focus must be on the nature of the crustal deformation process associated with different phases associated with the passage of typhoons and teasing out its contribution on tremor modulation or triggering mechanism. Further, some of the important questions that remain unanswered, which need to be addressed are: (a) Would tremor triggered by typhoon only occur in a particular area of Nankai, or could it happen in the other portion Nankai trough?

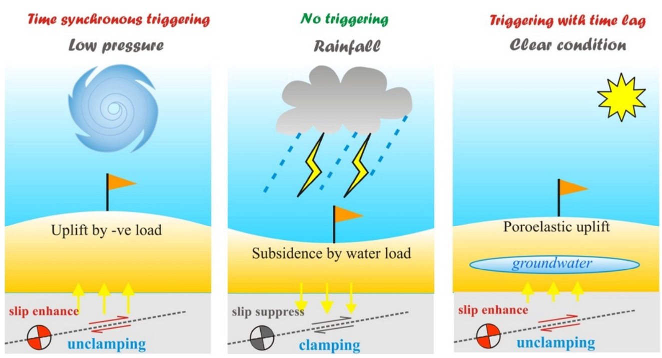

Fig. 3. Three phases of typhoon-induced vertical crustal movements (adopted from Zhan et al., 2021), its influence on the fault stability and tremor activation process (i.e., proposed hypothesis for typhoon-induced tremor modulation).

(b) Would tremor be modulated by typhoon for most cases? If tremor episodes can be easier triggered by typhoons, there could be more typhoon-triggering events, and finally (c) What is the typhoon-triggering threshold?

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