Slow Earthquakes in Taiwan

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Within the past two decades, a new generation of dense and sensitive earthquake-monitoring networks has led to a series of discoveries that have clearly revealed an entire class of slow earthquakes ranging in size from $M \sim 1$ to at least $M 7.6$ (Beroza and Ide, 2011).

What are slow earthquakes?

(Courtesy of Kelin Wang)
Episodic tremor and slip

Episodic tremor and accompanying slow slip are observed at the down-dip edge of subduction seismogenic zones.

(Rogers and Dragert, 2003)
Tremor is the seismic signature of slow slip

(Ide et al., 2007)
Detection challenge

1). Short: up to 37 minutes

Schwartz and Rokosky (2007)
Detection challenge

1). Short: up to 37 minutes

2). Weak: amplitude similar to noise
Regional earthquake swarms can also produce the tremor-like signals.
Ambient tremors in Taiwan have been previously catalogued for different purposes.

- A 4 yr catalog by Chuang et al. [2014], 8 month catalog by Idehara et al. [2014], and 134 day catalog from two dense arrays [Sun et al., 2015] for the characteristics of tremor activities; a 5.5 yr catalog by Ide et al. [2015] for moment tensor solutions in the very low frequency band and tidal sensitivity; 3 yr catalog for association with a M6.4 mainshock by Chao et al. [2017].
Outlines

How are the ambient tremors in Taiwan identified?
- comparison with other tremor catalogs (> 4 yr study period)

Where they are located?
- tectonic background
- why southern Central Range?

When did they happen?
- influenced by nearby earthquakes
- influenced by tidal stress
- influence by other natural source?

What is the hosting structure?

Problems and future Plan
Comparison of different detection scheme

<table>
<thead>
<tr>
<th></th>
<th>Chuang et al. (2014)</th>
<th>Ide et al. (2015)</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pro-processed data</td>
<td>2~8Hz, smoothed envelope</td>
<td>2~8Hz, Amplitude^2 &lt; 0.2 Hz</td>
<td>2~8Hz, Amplitude^2 &lt; 0.2 Hz</td>
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<tr>
<td></td>
<td>averaged horizontal components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time window</td>
<td>500 s</td>
<td>100 s</td>
<td>300 s</td>
</tr>
<tr>
<td>Time shift</td>
<td>300 s</td>
<td>50 s</td>
<td>150 s</td>
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<tr>
<td>ccc</td>
<td>&gt;0.95</td>
<td>&gt;0.5</td>
<td>&gt;0.6</td>
</tr>
<tr>
<td>Number of stations</td>
<td>&gt; 50% stations</td>
<td>&gt; 10 stations time residual &lt; 2s</td>
<td>&gt; 10 stations time residual &lt; 3 s</td>
</tr>
<tr>
<td>showing high</td>
<td></td>
<td></td>
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<tr>
<td>ccc &amp; small residual</td>
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<td></td>
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</tr>
<tr>
<td>SNR</td>
<td>&gt;1.15</td>
<td>NONE</td>
<td>&gt;1.2, &lt;30</td>
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<tr>
<td>Duration</td>
<td>&gt; 300 s</td>
<td>50% of max. amplitude</td>
<td>&gt; 60 s</td>
</tr>
<tr>
<td>Constraint on location</td>
<td>None</td>
<td>&lt; 1day; &lt; 10 km; Depth: 20-45 km</td>
<td>None</td>
</tr>
</tbody>
</table>

Chuang et al. [2014]: high criteria thresholds for waveform similarity and event duration

Ide et al. [2015]: removing the isolated tremors assuming they would cluster in space and time

Here we extracted a more complete tremor catalog by (1) including short-duration and isolated events and (2) excluding events that are too short to be discriminated from earthquakes.
In comparing these results with other tremor catalogs from the southern Central Range by Chuang et al. [2014] and Ide et al. [2015], we identified 5.4 and 3.7 times as many events during the same period, respectively.
The tremors are highly concentrated in the southern Central Range. They appear to occur below the seismogenic zone in the orogeny and show anti-correlation with shallow seismicity.
The relatively high frequency of tremors occurring in the middle of each year, revealing an annual variation. Between different catalogs, the notable difference occurred in mid-2009, where the Chuang et al. [2014] catalog is less active.
1. Temporal association with large earthquakes

- Temporal distribution of cumulative number of earthquakes that occurred within a distance of 10 km and 5 days prior to ($dt^-$) and following ($dt^+$) the tremor shows acceleration of tremor near the time of 2008 M5.2 and 2010 M6.4 earthquakes.
1. Temporal association with large earthquakes

- 2008 Taoyuan M5.2 event: 0.2 kPa
- 2010 Jiashian M6.4 event: 8 kPa
- 2012 Wutai M5.9 event: -0.3 kPa
- 2016 Meinong M6.4 event: 0.2 kPa
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Static stress triggering from nearby mainshock may not be the only factor responsible for tremor acceleration.
2. Tidal modulation of tremors

By applying power spectrum analysis for the hourly tremor duration, several sharp peaks appear that are correlated with tidal frequencies indicated by Darwin symbols such as Sa, Ssa, O1, S1, M2, S2, MO3, MK3, SK3, M4, and MS4.

More complete tremor catalog by including short-duration and isolated events.
2. Tidal modulation of tremors

(1) The maximum amplitudes of the tremor data however, occurred at the one year period (Sa), which is not seen in the tidal record.

(2) Msf, MO3/MK3, SK3, M4/MS4 are not clearly seen in the tidal spectra from gauges.

→ Artifact (Msf, MO3, M4)
→ other natural forcing source (Sa)
3. Other seasonal forcing

This periodicity in tremor activity coincides with times of rising ocean tides, decreasing air pressure, low ground water levels and minimal precipitation.
4. Hydro-mechanical coupling

When a vertical force equivalent to the rise of 2 m water load over an area of radius 50 km is imposed to the top of tremors centroid, the corresponding shear stress and Coulomb stress change at 25 km depth is on the order of -5 kPa and -4 kPa, respectively. (a)

The acceleration of tremors may occur in dry months due to unclamping of the fault and during the rain season the stress change acts to reduce tremor activity.

The stress induced by annual water loading may potentially have greater influence on tremor activity.
Why there?

Tectonic tremors occur in the middle of the Central Range south of Mt Yu, coinciding with the place showing progressive increase in thickness of subducting continental crust.

(Chang et al., 2000)
As continental crust of Eurasia is subducted it experiences prograde metamorphism that releases metamorphic fluids and weakens the surrounding crust.

As subduction continued, resistance increases along the plate boundary and strain localized in the weakened lower crust.

This leads to the development of a steeply dipping, crustal-scale shear zone.

Chen et al. (2018)
Problems & Future plan

- Identification (subjective and time consuming)
- Relocation (large uncertainties using different approaches, sparse network)
- Focal mechanism
- Other slow earthquake members?

Synthetic data
Problems & Future plan

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Synthetic data
Problems & Future plan

- Identification (subjective and time consuming)
- Relocation (large uncertainties outside the network)
- **Focal mechanism**
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Problems & Future plan

- Identification (subjective and time consuming)
- Relocation (large uncertainties outside the network)
- **Focal mechanism** (inconsistent results from different approaches)
- Other slow earthquake members?
Problems & Future plan

- Identification (subjective and time consuming)
- Relocation (large uncertainties outside the network)
- Focal mechanism (inconsistent results from different approaches)
- Other slow earthquake members? (SSE, LFE, VLFE)

During the common study period of 2007 to 2011 (1,826 events), we identified 40 VLFs with locations concentrated near tremor zone.

(Chen et al., 2018)
Acknowledgement

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Empirically, we discovered a pattern in total length and segments of the simplified amplitude of 1 that allows us to differentiate tremors from earthquakes.

Earthquakes are generally characterized by a smaller number of segments (<10) and shorter cumulative length (<30% of the 200 s window), while tremors and noise are characterized by a longer cumulative length (>30%) and larger number of segments (>30). This step allows us to exclude local or regional earthquakes that were included in the original detections.
When preparing the time series of hourly tremor duration, we introduced “zero” in the time series if no tremor occurred in that hour. To test whether such “tremor gap” may bias the periodic signal, we produced three truncate samples of time series using tidal stress calculation:

1. Frequency (1/hour)

   - (a) Observed data
   - (b) Synthetic data: become comparable to S1
   - (c) Synthetic data: cut off tidal shear stress < 0
   - (d) Synthetic data: cut off tidal shear stress < -1 kPa
   - (e) Tremor data

Shear stress: strike=60, dip=40, rake=90

Degree of truncation
(MO3) Spectrum of precipitation data

- the coupling between tidal level and rainfall
- possible contribution from hydrological loads at ~8 hours periods that is not seen in tidal records but in tremor data

(hourly precipitation)

M3 is also seen here

S1, S2
Very small MO3

Station distribution
- 20-Hz sampled seismograms (from three closest broadband stations) were first 2-8 Hz filtered, squared, 0.2 Hz low-pass filtered in a 1-Hz interval.

- The ambient noise reveals different behavior, suggesting the annual change of ambient noise has strong spatial variation due to local effect.
When a vertical force equivalent to the rise of 2 m water load over an area of radius 50 km is imposed to the top of tremors centroid, the corresponding shear stress and Coulomb stress change at 25 km depth is on the order of -5 kPa and -4 kPa, respectively. (a)

The acceleration of tremors may occur in dry months due to unclamping of the fault and during the rain season the stress change acts to reduce tremor activity.

The stress induced by annual water loading may potentially have greater influence on tremor activity.
Using the most updated tremor catalog from 2007 to 2012 (1893 events), we find tremor occurrence is strongly modulated by fluctuations in both shear and normal stress resolved on a fault plane of (strike, dip, rake) = (60°, 40°, 90°), from theoretical Earth and ocean tides. The percent excess number increases with tidal stress, reaching 150% at shear stress = 3.5 kPa.

Power spectrum analysis of the tremors reveals several sharp peaks that are correlated with semi-annual, semidiurnal, and diurnal constituents, which are shown in major tidal frequencies from nearby tidal gauges. The tremor peaks not seen in tidal records are likely an artifact during digitization (Msf, MO3, M4) and/or contribution from hydrological load (MO3).

There exists a significant annual variation in tremor activity. Increasing tremor activity is also found to coincide with times of increasing tides, lowering of groundwater and air pressure, and relatively low precipitation. The amplitude of shear stress due to water load change is potentially greater than tidal stresses, suggesting that the role of hydrologic load may be as/more important.
Slow slip events

(Liu et al., 2009, Nature)
(Chen et al., 2018, JGR)
Triggered tremors

(Peng and Chao., 2008)

(Chao et al., 2011)
This change in thickness of continental crust projects to the core of the Central Range in Taiwan where the highest peaks reach 3952 m (Mt Yu).
Why there?

East-west and orogen-parallel sections of the Vp/Vs models show the tremors distributed along the boundary between relatively high and low Vp/Vs values, consistent with previous interpretations that suggest a relation between tremor activity and fluid flow.
The southern CR is also characterized by rapid uplift rate of 1-2 cm/yr.
Normal faulting earthquakes

Extensional environment
Why southern Central Range?

Greater geothermal gradient
(Hsieh et al., 2014)

Low electrical
(Bertrand et al., 2012)

Deep fluid source (0.4~1.4% fluid content)
Why southern Central Range?

**Magnetic anomaly**

(Magnetic anomaly (Modified from Yen et. al., 2008))

**Low Q**

(Wang et al., 2010)

Tremor zone (20-40 km at depth):
fluids & high temperature

Above the tremor zone (< 20 km):
extensional environment
Tectonic explanation (simple version)

Enough subduction to produce metamorphic fluids

Enough extension to accelerate their release

Crustal detachment and extension accelerates the fluid release

Subduction leads to metamorphism which makes fluids

Chuang et al. (2014)

Swarm/tremor source is located at where slab breakoff took place

V_p from Rau (1995)
VLFE derived focal mechanism

- cross correlation > 0.5 for ≥ 10 station pairs
- minimize the square of misfits btw. obs. and cal. Time (<2s)
- relocation

The sum of theoretical ocean and solid Earth tidal stresses
Stacking amplify the tremor signals

1. Stacked similar waveform
2. Take average amplitude of stacked waveform

SNR time series of each station
Tremor as the seismic signature of slow slip

Geodetically determined seismic moment scales with the total duration of tremor

(Aguiar et al., 2009)
Magnitude of possible slow slip events?

Ordinary earthquake:
Mo ~ duration³

Slow earthquake:
Mo ~ duration

Moment equivalent to M4.1-5.6 events

[Ambient tremor events in this study

[Beroza and Ide, 2011]
Summer Tremor Activity Seminar

Nonvolcanic Tremor Deep Beneath the San Andreas Fault near Cholame,

Volcanic tremor: An overview

Space and time behavior of non-volcanic tremor in the southwest Japan subduction zone

Low-frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip

Mechanism of slow/silent slip events in subduction zones:
Insights from 3D modeling

Vedran Lekic

24 August (Thursday) 3:00 pm
Room 220

recurrence intervals and possible mechanisms

Mei Xue

17 August (Thursday) 3:00 pm
Room 220

David Shelly
Ph.D. Candidate, Geophysics
Stanford University

3 August (Thursday) 4:00 pm
Room 220

10 August (Thursday) 3:00 pm
Room 220