Detection and location of non-volcanic tremor beneath the Central Range in Taiwan

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Introduction

Volcanic tremor is a long-duration episode of weak seismic motions without distinct P or S phases, often observed in volcanic and geothermal area. Non-volcanic tremor is a similar seismic signal observed away from volcanic regions (Obara, 2002), with an extended duration, vague body wave onset and spectra depleted in high-frequency energy (Peng and Chao, 2008).
So far non-volcanic tremor events have been observed and located worldwide. In southwest Japan, tremor is distributed throughout the Tokai, Kii, and Shikouku regions for 600 km along the strike of subducting Philippine Sea Plate, at depths of 30-45 km on the plate interface (Obara, 2002). In Cascadia, tremor is detected on the deeper (25- to 45-km) part of the northern Cascadia subduction zone interface, from Vancouver island to northern California, with a distance of over 1000 km (Rogers and Dragert, 2003). Apart from that, similar events have also been identified in other subduction zones, such as Alaska (Peterson and Christensen, 2009), Mexico (Payero et al., 2008), Costa Rica (Brown et al., 2009), Taiwan (Peng and Chao, 2008), and San Andreas fault system (Nadeau and Dolenc, 2005; Gomberg et al., 2008).
The importance of the non-volcanic tremor study is that tremor is located on the transition zone of the plate interface, which is just next to the fast slip zone where large mega thrust earthquakes take place. Since tremors are very sensitive to small stress change on transition zone, so we hope to find some connection between mega thrust earthquake and non-volcanic tremor.
We can divide non-volcanic tremors into two types: ambient tremor and triggered tremor. When a tremor is triggered by teleseismic event during the passage of its surface wave, we tend to define it as triggered tremor. By ambient tremor, we are simply referring to tremor occurring naturally.
My work mainly focuses on the Island of Taiwan. Its active seismicity and high density seismic network are helpful for the non-volcanic tremor study. What is more,
the tectonic condition in Taiwan is very unique. It is located in the convergent plate boundary zone where the Philippine Sea plate has obliquely collided on the Asian continental margin. Two subduction zone systems of opposite polarity are juxtaposed under the central Taiwan: to the northeast the Philippine Sea plate (PSP) is under thrusting beneath the Eurasian plate (EP), while to the south the EP is subducting eastward beneath the PSP. Therefore non-volcanic tremor study in Taiwan will promote our understanding in geodetic configuration and fault mechanics in Taiwan. (Peng and Chao, 2008)

Data and Detection

My analysis used 3 types of seismogram data:
1) CWB data: short-period (1-Hz) velocity seismometers operated by the Central Weather Bureau Seismic Network (CWBSN).
2) BATS data: Broadband Array in Taiwan for Seismology (BATS) operated by the Institute of Earth Sciences (IES) at Academia Sinica in Taiwan.
3) Array data: temporary velocity seismometers operated by Earthquake Research Institute.

All of the stations are equipped with three-component instruments, and the sampling rates are 100 Hz, 20 Hz and 200Hz for CWBSN, BATS and Array data, respectively.

Figure 1. Map of Taiwan Seismic stations based on the topography map of Taiwan.
Triangles represent permanent stations including both BATS and CWB data. Stations marked with circles are temporary Array stations, which has an approximately linear distribution.

Original data has a time length of 1 day. Firstly, I removed the mean and re-sampled the data to 1Hz, and then applied a 2-8Hz band-pass filter and generated the envelope data. In order to detect the tremor signal more conveniently, I cut the 24-hour data with a time length of 1 hour so that I can observe the seismic signal more clearly in every 1-hour time window. Finally, by combining every single data into a multi-trace envelope plot, we could detect tremor signal.

With this method, I succeeded to detect 14 tremor sequences from a period of about two months from March to May, 2005 (Table 1). The duration of detected tremor sequences ranges from 10 to 26 minutes. Table 1 is the tremor catalogue I generated based on observation and multi-trace envelope plot.

These detected tremors include not only ambient tremor but also triggered tremor. Ambient tremor (Figure 2) is characterized by coherent envelopes with complicated shapes for many stations. Triggered tremor (Figure 3) has periodic envelope peaks with an interval of 20 seconds according to the long-period surface wave from the large teleseismic event.

**Table 1.** Tremor catalogue

<table>
<thead>
<tr>
<th>Date</th>
<th>Begin Time</th>
<th>End Time[sec]</th>
<th>Duration[sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005/03/12</td>
<td>22:21:40</td>
<td>22:35:40</td>
<td>840</td>
</tr>
<tr>
<td>2005/03/19</td>
<td>20:24:00</td>
<td>20:50:00</td>
<td>1560</td>
</tr>
<tr>
<td>2005/03/28</td>
<td>16:21:40</td>
<td>16:41:40</td>
<td>1200</td>
</tr>
<tr>
<td>2005/03/29</td>
<td>14:43:20</td>
<td>14:57:20</td>
<td>840</td>
</tr>
<tr>
<td>2005/04/05</td>
<td>20:10:00</td>
<td>20:20:00</td>
<td>600</td>
</tr>
<tr>
<td>2005/04/07</td>
<td>20:10:00</td>
<td>20:20:00</td>
<td>600</td>
</tr>
<tr>
<td>2005/04/17</td>
<td>17:30:00</td>
<td>17:40:00</td>
<td>600</td>
</tr>
<tr>
<td>2005/04/17</td>
<td>19:36:50</td>
<td>19:56:50</td>
<td>1200</td>
</tr>
<tr>
<td>2005/04/19</td>
<td>22:15:00</td>
<td>22:29:00</td>
<td>840</td>
</tr>
<tr>
<td>2005/04/20</td>
<td>19:06:40</td>
<td>19:32:40</td>
<td>1560</td>
</tr>
<tr>
<td>2005/05/08</td>
<td>10:00:00</td>
<td>10:18:00</td>
<td>1080</td>
</tr>
</tbody>
</table>
Figure 2. Multi-trace envelope plot on 2005/03/19. The envelope is generated after resampling and a 2-8 Hz band-pass filter. According to the envelope shape, we can define it as an ambient tremor.
Figure 3. Multi-trace envelope plot on 2005/03/28. The envelope is generated after resampling and a 2–8 Hz band-pass filter. The multi-trace envelope is compared with the transverse and radial component broadband and 2–8 Hz bandpass-filtered velocity seismograms recorded at the Array station ST24. The radial component is more alike
to the envelope plot, which can be the evidence of the Rayleigh wave triggered tremor.

Moreover, the triggered tremor (Figure 3) occurred on 29th March has already been discussed in previous research (Tang et al., 2010), indicating that the tremor was triggered by the 2005 MW8.6 Nias Earthquake off the coast of northern Sumatra. Some detailed information about Nias earthquake is listed as follow in Table 2.

Table 2. Nias earthquake

<table>
<thead>
<tr>
<th>TIME</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>DEPTH</th>
<th>MAGNITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005-03-28</td>
<td>2.10</td>
<td>97.11</td>
<td>30</td>
<td>8.6</td>
</tr>
</tbody>
</table>

We can observe some other interesting signals through the multi-trace envelope plot. In Figure 2, we can find a very unique signal in station ST30 around 240 seconds, which is not coherent in other stations nearby. We often regard such kind of signal as noise. In Figure 3, around 720 seconds, there is a spikey signal clearly observed in many stations, and we can even see the body-wave onset in stations ST18, ST19, and ST21. We define such kind of signal as regular earthquake or body wave phases of the teleseismic event.

**Result**

Since it was very difficult to identify the initial P- and S-wave onset for tremor location, what I applied in this case was the envelope correlation method (ECM) (Obara, 2002). Firstly I applied cross-correlation in time domain to get the time lag of maximum correlation coefficient between each station pair. After that, I obtained the spatial distribution of the relative arrival time of the envelope. The observed relative arrival time data was used to determine the hypocenter of the tremor.
As mentioned below, the geodetic configuration in Taiwan is very complicated, even though we have concluded that tremor events often take place near or on the subducting slab interface, it is hard to determine a precise depth for tremor in Taiwan. Therefore, in my location method, I fixed the depth at 25km. I used the grid-search method in a homogenous velocity model ($V_s = 3.5$ km/sec) to locate the epicenter of tremor. After grid subdivision, I set the grid point with the smallest deviation between the theoretical and observed time lag as the location of tremor event.
Figure 5. Theoretical time lag between each station pair with the smallest deviation compared with the observed one (Figure 4).

I calculated the tremor location every 2 minutes, and the time window was shifted every one minutes. And finally I obtained the tremor location for the catalogue in Table 1.
Figure 6. Tremor distribution calculated from grid search method. Red circles are the locations measured every 2 minutes, and the white ones are the average of every single tremor event according to the tremor catalogue in Table 1. It is plotted on the topography map of Taiwan.

As for triggered tremor, we can even get a very good correlation result in each burst of the tremor episode. In that case, I was able to locate the tremor based on every burst. Compared with the 2 minutes’ time window, it was more precise in terms of location.
Figure 7. Location results for different time windows, red circles represent the solutions for 2 minutes’ time window, and the white ones are locations calculated for every burst.

Compared with previous result on the study of triggered tremor on 28 March, 2005, my result is quite consistent with the previous one. Thinking of the densely distributed seismic stations, we have confidence in the high accuracy in our results.
Figure 8. Locations of low frequency earthquakes (dark green circles) within tremor triggered by the passing surface waves of the 28 March 2005 Mw8.6 Nias earthquakes. Squares and triangles represent the stations used in this study within the Broadband Array in Taiwan for Seismology (BATS) and the Central Weather Bureau Seismic Network (CWBSN), respectively. The cross section line AA’ marks the direction perpendicular to the Central Range (CR). The blue line marks the surface expression of the Chaochou-Lishan fault (CLF). The Longitudinal Valley (LV) suture is located in the east side of the CR. The inset shows the epicenter of the 2005 Mw8.6 Nias earthquake and the great circle path to the study region (square) (Tang et al., 2010).

Discussion

By comparing different envelope plots between ambient tremor and triggered tremor, we can conclude some features about ambient tremor and triggered tremor. It is often the case that triggered tremor signal is more significant than ambient tremor signal, due to its higher signal-to-noise ratio. Unlike triggered tremor, ambient tremor, often accompanied with slow slip event, doesn’t appear modulated by waves of teleseismic events. However, there is evidence that triggered and ambient tremor are actually sharing very similar focal mechanisms: reflecting shear slip on the plate interface with the same sense of slip as that expected from plate motions. Both of their envelopes have gradual rise time other than the spike-like shape of normal earthquakes.

Taking Taiwan’s high seismicity into consideration, where tremors occur is a relatively quite area in terms of seismic activity. And such result is also consistent with the background knowledge that tremors are located on the transition zone right next to the seismogenic zone where large earthquakes occur.

At present, there are two models (Figure 9) trying to explain the geodetic configuration beneath Taiwan, which belong to different types of fault: Reverse fault model and Left-lateral strike-slip fault model.
If we are able to get tremor locations with high accuracy based on densely distributed array data, especially on depth, we can conclude which type of fault is beneath the central range in Taiwan.

Figure 9. Multiple tremor source models: Type I: A reverse fault model with high- or low- (60° or 15°) dipping angles. Type II: A low-angle oblique-slip fault plane model with high or low dipping angles. (Chao et al., 2012)

To understand the geodetic configuration beneath central range in Taiwan, there is a lot of work can be done to improve my research. Since the array stations are so densely distributed, we may possibly get more precise information on depth, which calls for a finer velocity model beneath Taiwan and a better grid search method. In that case we can have a better understanding of the geodetic configuration in Taiwan and the focal mechanisms for tremor as well. Therefore our future work will concentrate on improving the location method by using the array data to explain the tremor source model.

References


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