Array-analysis of Tremors in Shikoku Triggered by the 2012 Sumatra Earthquake

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Abstract

This study has successfully located earthquake tremors in Shikoku area triggered by the teleseismic surface waves of the 11th April 2012 Sumatra earthquake using array-analysis method (MUSIC). Results show that the first and the second part of the detected triggered tremors are located in different regions of the Shikoku area, as triggered respectively by Love- and Rayleigh-wave. The physical mechanisms of the two events are supposedly different. Frequency analysis of the two parts of seismograms are conducted to demonstrate the difference, showing that dominant frequencies appear in the second part of seismograms, as representing the up-dip side tremors in Shikoku area which might be caused by fluid migration in the interface of the subduction zone. However, this phenomenon is not well explained and requires a further understanding.

Introduction

Non-volcanic tremors are a kind of slow earthquakes, which is a family of inter-plate phenomena in subduction zones, including short-term and long-term slow slip events (SSEs), deep and shallow very-low-frequency earthquakes (VLFs) as well. Non-volcanic tremors were first detected in Nankai subduction zone (Obara, 2002) and later detected in other parts of the world, including Cascadia (Rogers and Dragert, 2003), 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). It has become the most significant and exciting geophysical discoveries of the 21st century (Obara, 2011).

Tremors are different from other earthquake phenomena in the following aspects:
it is a family of weak seismic events with small magnitude (~1), causing no damaging effects; the seismic signals of tremors are lack of clear P- and S-waves, with a predominant frequency of 1-10Hz, which is far lower than regular earthquakes of similar magnitudes; this seismic event usually has a long duration (up to several days) and a periodicity of occurrence (3-20 months); the distribution areas of tremors are segmented in local regions; tremor signals are accompanied by SSEs (always, yet sometimes undetected) and VLF earthquakes (sometimes).

Besides these characteristics, there is another feature of tremors: tremors are likely to be triggered by teleseismic surface waves. These signals are called “triggered tremors”, relative to “ambient tremors” that are spontaneous seismic events near subduction zones.

Our study focuses on the triggered tremors of the Shikoku area, Japan. After the 11th April 2012 Sumatra earthquake, a cluster of tremor events are detected in Shikoku area (Figure 1). Around 800s after the P-wave arrival, 21 tremor events are observed. Comparing with the observation of low-frequency seismograms, the tremors are supposedly triggered by the Love and Rayleigh waves of the Sumatra earthquake. Meanwhile, we find the first and second part of the tremor wave train are slightly different and might be triggered by different kind of surface waves. To obtain a supporting evidence of this idea, it is important to analyze the location of these tremor events.

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![Tremor signals triggered by teleseismic surface wave](image)

Different from the traditional ECM method, in this study an array-analysis method (MUSIC) is applied. MUSIC (MUltiple SIgnal Classification) method is first raised by a member of IEEE (Schmidt, 1986). It is famous for high resolution and good anti-noise ability. In seismic study, this method is widely used in the analysis of rupture process of big earthquakes. We have applied MUSIC in the location of triggered tremors in this work and found the difference in location of the first and second part of observed tremors. In a further step, the physical mechanisms of the two events are supposedly different. Frequency analysis of the two parts of seismograms
are conducted and discussed in later part of this paper.

**Data Processing**

Seismic data from 4 station arrays are used in this study. The location and distribution of the four arrays are shown in Figure 2. There are respectively 29, 7, 26, 6 stations in array 1-4. Each array has a special distribution of a one/two km-wide square.

![Figure 2 | Distribution of station arrays](image)

![Figure 3 | Aligned tremor signals in Array 1](image)
The filtered seismic data (2-8Hz) of a specific array are carefully aligned by calculating the best correlation coefficient. The aligned data is shown in Figure 3 (Data from Array 1). Clear tremor bursts could be identified in the figure, each tremor burst lasts around 20-30 seconds. The tremor signals are put together of the same start-time with the low frequency component of the seismograms, as is shown in Figure 4. Good correlation of tremor bursts and surface wave could be clearly identified in the first part of wave train, however, in the second part, a time-delay is observed. This indicates that the first part (10 tremor bursts) and the second part (11 tremor bursts) are located in different regions.

![Figure 4](image)  
*Figure 4 | Correlation of tremor signals and surface wave*

**The MUSIC Method**

MUSIC (Multiple Signal Classification) is an array-analysis method in signal processing. It is widely used in studying the rupture process of big earthquakes and is famous for high resolution and good anti-noise ability. Different from traditional methods, MUSIC is based on the Eigen-decomposition of the received signal matrix. By carrying out the Eigen-decomposition, the matrix-generated space is divided into two subspaces: the signal space and the noise space. These two spaces are orthogonal, which then facilitates a “peak-forming” process.

The steps for carrying out MUSIC method are summarized as follows:

**Step 1**  Filter and align the received seismograms. Transfer them into frequency domain

**Step 2**  Form the correlation matrix $R$. Eigenvalue-decompose $R$, obtain noise space $U_N$

**Step 3**  Set the grids in rupture area. Determine the phase-shift vectors $\bar{T}_k$ for each grid

**Step 4**  Form $P_{\text{MUSIC}}$ for frequency $\omega_k$ on grid $k$ by

$$P_{\text{MUSIC}}(\omega_k, k) = \frac{1}{\alpha_s(\omega_k \bar{T}_k - T_0)^H U_N U_N \alpha_s(\omega_k \bar{T}_k - T_0)}$$
Step 5 Normalize $P_{\text{MUSIC}}$ into $P_{\text{norm}}$

Step 6 Calculate the energy emission $E(\omega)$ of the current frequency

Step 7 Stack $P_{\text{norm}}E(\omega)$ throughout the analyzed frequency range, get the final $Q$

Results

Using one array data, the direction of potential tremor location could be obtained. For each tremor burst, a direction is yielded using MUSIC method. Stacked results for the first and the second part of tremors are shown in **Figure 5** & **6**. The red area represents the most potential directions of tremor location. Blue part in the left shows the data used in conducting MUSIC method.

**Figure 5 | Stacked MUSIC result of the first part of tremors**

**Figure 6 | Stacked MUSIC result of the second part of tremors**
From Figure 5 & 6, a clear difference in direction could be seen, which approves of our hypothesis that the two parts are located separately. The first part is located upward (down-dip) and the second part is located downward (up-dip).

Using multiple arrays, the location of tremors could be obtained by stacking the four single-array results. Final results are shown in Figure 7. Ambient tremors are also plotted in the same figure. We can see that the triggered tremors are located in the

![Figure 7 | Result of multiple arrays](image)

![Figure 8 | Amplitude ratio of tremor bursts, array 2 to array 4](image)
ambient tremor zone, while the first part lies upward and the second part lies downward in the map. Removing the outliers (one each in the first and second part), we calculate the average location of the two parts of tremors, as demonstrated in colored stars. The averaged two locations of the two part have a distance of around 5km.

The amplitude ratio of tremors of array 2 to array 4 is calculated for each burst (Figure 8). In the first part, the amplitude ratio is lower than 1, which means that the tremors of the first part are located nearer to array 4 than array 2; meanwhile, the amplitude ratio of the second part is relatively larger, which shows that the tremors of the second part lie nearer (or equally) to array 2 than array 4. This analysis supports our previous result.

Discussion

Our results show that the first and second half of tremor bursts are located in different regions: the first half is located in the down-dip direction while the second half is located in the up-dip direction. This difference in location suggests that the two tremor clusters are of different physical mechanism. In observation, within each segment, active tremor bursts are mainly concentrated at the up-dip edge of the tremor zone, which are often associated with higher energy emission; down-dip tremor, on the other hand, is characterized by frequent recurrence (Figure 9, Obara, 2011).

**Figure 9 | Observational Features of earthquake tremors**

The first and the second half of tremor bursts are triggered by Love wave and Rayleigh wave respectively. Previous study shows that tremors triggered by Love wave (observed in Cascadia and Taiwan) are caused by increased coulomb failure stresses which promote slip on the plate interface (Rubinstein et al., 2007; Peng and Chao, 2008); tremors triggered by Rayleigh wave (observed in Nankai subduction zone) are incurred by brittle fracture, which is induced by fluid migration caused by...
Figure 10 | Frequency Spectrum of the first and second tremor cluster
variations in volumetric pore space (Miyazawa and Mori, 2006). Since slip on the plate interface is related to frequent recurrence of down-dip side tremors, and fluid migration is dealt with high energy emission, the observational features match with the tremor-triggering mechanism. This supports our hypothesis that the two tremor clusters come out of different physical mechanisms.

To further prove our hypothesis, the frequency spectrum of the two tremor cluster is shown in Figure 10. The seismograms of one array are stacked and a frequency spectrum is yielded for each array. Two features could be seen in the figure: 1) much low-frequency components of the 2nd part; 2) predominant frequency of the second tremor clusters could be identified of each array. As for the first point, we re-examined the mid-frequency components of the seismograms and discovered an earthquake event within the second part of the wave train (Figure 11). This might explain why lower frequencies are dominant in the second tremor clusters. However, there is no thorough understanding of the predominant frequency. One wild guess is that the direction-relied predominant frequency is somehow related to the direction of dilatational stress, which is the supposed mechanism of the second tremor cluster.

**Conclusion**

This study focuses on the location of tremors triggered by the 11th April 2012 Sumatra earthquake using the MUSIC array-analysis method. The main result is that the tremor clusters triggered by Love wave and Rayleigh wave respectively are located in different regions of the Shikoku tremor zone. The difference in location suggests different physical mechanisms of the tremor clusters. The correspondence of the observational features of tremor and the tremor-triggering mechanism supports the mentioned idea. The frequency spectrum analysis serves as another proof of the hypothesis, although some further understanding is required to fully explain the phenomenon in the frequency spectrum.
References


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