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Long-term Research Visits (Project No.: 30L-03)

Project name: Studying non-earthquake signals recorded at seafloor OBS stations, as related to natural hazards and natural resources
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Research period: January 10, 2019 ~ February 28, 2019
Research location: DPRI, Uji
Number of participants in the collaborative research: 2 1 DPRI (faculty), Dr. James Mori
1 non-DPRI (researcher), Dr. Takashi Tonegawa

- Number of graduate students: (provide numbers for Masters and Doctoral students)
  none*
- Participation role of graduate students [ ]
  * During the period of this project, two Taiwanese research assistants work with PI in National Taiwan University. These two assistants have already obtained their master degrees. Both tend to access PhD programs in the next few years. One of them has already requested the PhD admission in the Institute of Oceanography (National Taiwan University) in April, who will follow the T-wave study initializing in this project.

Anticipated impact for research and education

This project aims to advance the study of seafloor geological activity which is known to play an important role in the offshore natural hazards and resources. A few subjects extending from this project can enhance the knowledge of the related domains and lead a few graduate students to the further scientific explorations.

Research report

(1) Purpose

At the present, Ocean bottom seismometer (OBS) is common to receive seismic signals that is located at or near the seabed. Comparing to the in-land seismic stations, the seismic waves recorded at the seafloor stations can propagate not only through the solid earth but also the water column and the water-sediment interface. The recent studies reveal that the unconventional non-earthquake signals recorded at OBS stations can be a proxy to study seafloor geological processes (e.g. Stehly et al., 2006; Géli et al., 2008; Tary et al 2012; Chang et al. 2016), which link to important issues of natural resources and seismic hazards in offshore areas. In this project, our focus is lay on two distinct signals recorded at the OBS stations: the bubble signals and the T waves.

In terms of seafloor geological processes, natural gas emissions from the seafloor are a common phenomenon that occurs worldwide. Along the OBS seismogram, the waveforms of gas emission signals exhibit a high-frequency resonant vibration alike the bubble bursting at the free surface of a non-Newtonian fluid. The typical bubble signals are the very local energy onsets which are detected only at one OBS station which is very close to the venue of gas emission. A single bubble waveform can be roughly described as a cosine wave chain rapidly attenuating in a period less than 2 seconds. However, the efficiency of the mathematical matching is very limited. Considering the bubble waveforms can be easily identified by a trained seismologist, the Machine Learning (ML) skill will be a good alternative approach in this task.

On the other hand, T waves propagate in the SOFAR channel of minimum sound velocity acting as a wave guide for acoustic energy in the world's oceans. They can be excited by sources in the solid Earth such as earthquakes through conversion of seismic energy into acoustic waves at the solid-liquid interfaces. Within the

OBS data acquired from the northern South China Sea, The T-wave events can be located at the deep-sea seamounts or the feature zone of the spreading system, which are far below the SOFAR axis minimum. Actually, With the recent increase of OBS deployments worldwide, T wave detection in deep ocean regions below the SOFAR axis minimum has become abundant. The mode theory which describe coupling between elastic and acoustic modes under scattering by structural heterogeneities located at the ocean bottom, and which are becoming increasingly successful at modeling the wave shapes of abyssal T phases is adopted in this study. In practice, the numerical code SPECFEM2D based on a spectral element method is used to model the generation and propagation of the T waves. Furthermore, the measurements combining the amplitude and duration of T waves can yield information on source rupture, and more specifically detect the presence of source mechanism.

The OBS data used in this project are acquired from the northern South China Sea (mobile short-period OBS arrays), offshore Japan (mobile OBS arrays and the Donet network), and also the Lesser Antilles subduction zones (mobile short-period OBS arrays). Besides the geological environment of convergent plate boundaries (such as Taiwan and Japan), these data are also applied to consider the offshore seismic hazards and kinetic energy dissipation in the ocean.

(2) Summary of research progress

We specifically study the bubble signals and the T waves which embed within the OBS seismograms. Below are the main approaches.

I. The bubble signals

In terms of seafloor geological processes, natural gas emissions from the seafloor are a common phenomenon that occurs worldwide, e.g. in coastal deposition environments, delta fan deposits, hydrocarbon-bearing sedimentary basins and accretionary prisms (Judd and Hovland, 2007). The gases emitted at seafloor are principally composed of methane and fluid seeps can include hydrocarbons. The importance of these emissions for a number of societal (e.g. the assessment of the contribution of submarine methane sources in gas global budgets) and environmental issues (e.g. hydrocarbon leak detection) conducting to economic ones, has fostered the interest of the scientific community for understanding the natural degassing processes from the seafloor.

The recent years we collaborate with the French Ifremer group in studying the seafloor bubble signals. Based on the Ifremer OBS experiment on the Marmara seafloor, along the North Anatolian Fault zone, a single bubble can be characterized by durations of less than 0.8-s, by frequencies ranging between 4 and 30 Hz, by highly variable amplitudes and by one single-wave train, with no identified P- nor S-wave arrivals (Geli et al., 2008). The presence of gas in superficial sediments, together with analogies with laboratory experiments, has led Tary et al (2012) to suggest that gas migration followed by the collapse of fluid filled cavities or conduits could be the source of the observed microevents. Acoustic data from a seabottom bubble detector (Bayrakci et al, 2014) and geochemical data from a methane sensor (Embriaco et al, 2013) provide additional evidence supporting the hypothesis that the bubble emergence could be related to degassing processes from the seafloor

Quantitative methods have been developed as to characterize gas releasing from the seafloor into the water column (e.g. Wheeler and Gardiner, 1989; Sills et al., 1991) or provide the in-situ observations combining the use of gas flux-meters and pore-pressure (e.g. Boles et al., 2001; Leifer and Boles, 2005; Kopf et al., 2010). Remote, water column acoustic studies are also carried out with the use of a towed or hull-mounted sonar systems (e.g. Merewether et al., 1985; Dupré et al., 2010; Greinert, 2008). In this study, we tried to develop the computer algorithm detect the bubble signals by both mathematic fitting and Machine Learning (ML) skill.

The typical bubble signals are the very local energy onsets which are detected only at one OBS station which is very close to the venue of gas emission. A single bubble waveform exhibits a high-frequency resonant wave chain and a bursting at the free surface of a non-Newtonian fluid. Each single bubble vibrates generally less than 2 seconds. Because this signal coming from the gas emission from the ground, the geophone components can better record its waveform than the hydrophone one. Based on the character of mono-tone resonant vibration and quick attenuation, we have roughly described the bubble waveform as an attenuated cosine wave chain, which is,

$$F(t)=\boldsymbol{A}\cos(2\pi \boldsymbol{f}\, t)\, \exp(\boldsymbol{a} t)$$

F(t) is the time series of bubble waveform; ***A***, ***f*** and ***a*** are the maximum amplitude, specific mono-tone vibration frequency, and attenuation rate of each bubble. This mathematical matching can help to identify the bubble waveforms from the continuous OBS seismogram. By means of mathematical matching, we can have 459 bubbles. By these found bubble waveforms, the resonant frequency and attenuation rate are determined as 5.2~5.8 Hz and -1.8 ~-1.0 count/sec, respectively.

In fact, the OBS seismogram is commonly full of noise and unknow signals, which disturbs the mathematical matching. The efficiency of the mathematical matching is therefore very limited. Considering the bubble waveforms can be easily identified by a trained seismologist, the ML skill will be a good alternative approach in this task. In this project, we establish a convolutional neural network (CNN) structure to classify the OBS amplitudes into the bubble signals from the others. By means of the ML algorithm, this subject may be carried out quickly and efficiently.

A key issue in developing a ML model is to train model with a large dataset. By means of the resonant frequency and attenuation rate retrieved from the previous process, we create over 40,000 synthetic bubbles and use them to compose a well-trained ML model. At the moment, we try to insert various scenarios for the synthetic waveforms (for instance, different noise levels, bubble-alike waveforms, etc) and refine our training. The detection efficiency of the ML model will be discussed soon.

II. T waves

T waves propagate in the SOFAR channel of minimum sound velocity acting as a wave guide for acoustic energy in the world's oceans. They can be excited by sources in the solid Earth such as earthquakes through conversion of seismic energy into acoustic waves at the solid-liquid interfaces. Actually, with the recent increase of ocean-bottom seismometer (OBS) deployments worldwide, T wave detection in deep ocean regions below the SOFAR axis minimum has become abundant (Butler and Lomnitz, 2002; Okal, 2008; Ito et al., 2012). A theoretical explanation may be given by Park et al.'s (2001) mode-coupling model, which states that the higher modes of acoustic oscillation couple with bathymetry, through this process T wave energy can reach the seafloor. In this project, we model the generation and propagation of such acoustic waves, using the numerical code SPECFEM2D based on a spectral element method (Tromp et al., 2008). The simulations of an explosion source in the western Japan Sea is set to make the first trial in this study. We aim to reproduce the T waves provoking by the 2017 North Korean nuclear test. Synthetic signals will be then studied at different spreading distances and compared to the associating T-wave signals recorded at the in-land F-net seismic stations.

(3) Summary of research findings

All the analyses are under processing. Below list the results obtained so far.

The bubble findings

Figure 1 demonstrates a typical seafloor bubble. In general, the bubble signals can be better recorded at the geophone than hydrophone. It can be inferred that the bubble signals coming from the strata rather than the water. By means of mathematical matching, we can have 459 bubbles. In Figure 2, the resonant frequency of the bubbles is about 5.2~5.8 Hz; the attenuation rate is -1.8 ~-1.0 count/sec.

Figure 3 shows the examples of the synthetic waveforms. The accuracy of the ML model trained with the synthetic waveforms can achieve 100% for the synthetic data. However the accuracy drops down very quickly when the background noise level increases. We shall refine the ML model with more bubble waveforms of varied conditions.

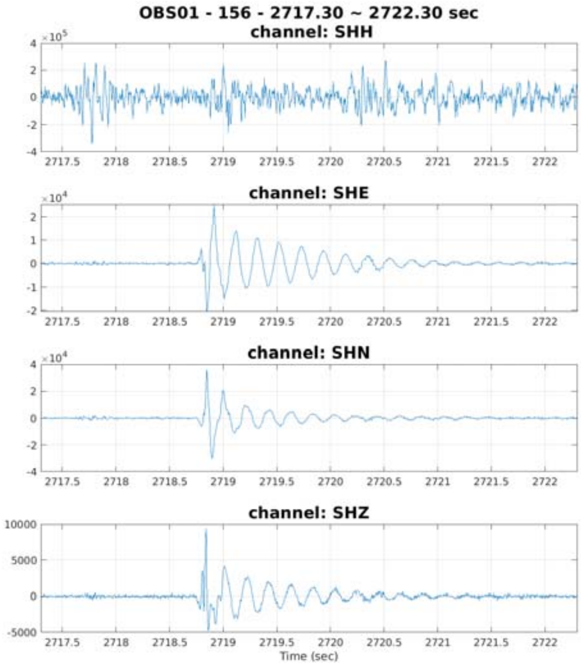

Figure 1. The demonstration of a typical bubble waveform at four channels. From top to down: hydrophone, horizontal-EW, horizontal-NS, and vertical channels. Here the recording azimuths of two horizontal records are not corrected.

(a) (b)

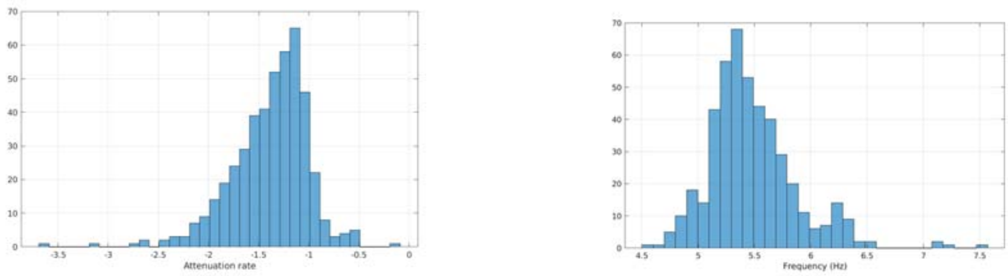

Figure 2. The histograms of the mathematical coefficients of bubble waveforms: (a) attenuation rate, (b) resonant frequency. The Y axes are event numbers.

T-wave simulation

The objective is to set a physical model as close as possible to a real case to compare synthetic seismograms with actual T waves recorded at seafloor and in-land seismic stations. In the first test, we check the T waves propagating over the whole Japan Sea in an acoustic mode. Figure 4 illustrates the targeted sites set in this simulation. The effect of geometric spreading is discussed with the different propagating distances. Because our code is two-dimensional (2D), our simulation is done in the vertical planes passing through the source and each of the targeted sites. Figure 5 shows the preliminary resultant waveforms, which are carried out with a non-stratified water layer and the flat topography. The energy source is taken as a simple explosion which wavefield is radiated and reflects the pressure pulse in the far field. In Figure 5, the Groups A, B, and C are the sites at the near shore of the western Japan, middle, and western Japan Sea, respectively. We can see a systematical change in T-wave amplitude varying with the spreading distance (Here the distance: Group C < Group B < Group A).

In the next test, more physical properties of water, such as kinematic dissipation, attenuation, as well as the seismic-wave conversion between solid earth and water shall be taken into account. By means of this study, we can achieve a comprehensive understanding for the wave propagation within the shallow media of the earth. It is important for the study of all seismic sources and, in particular, the physical interaction in-between the solid earth and water.

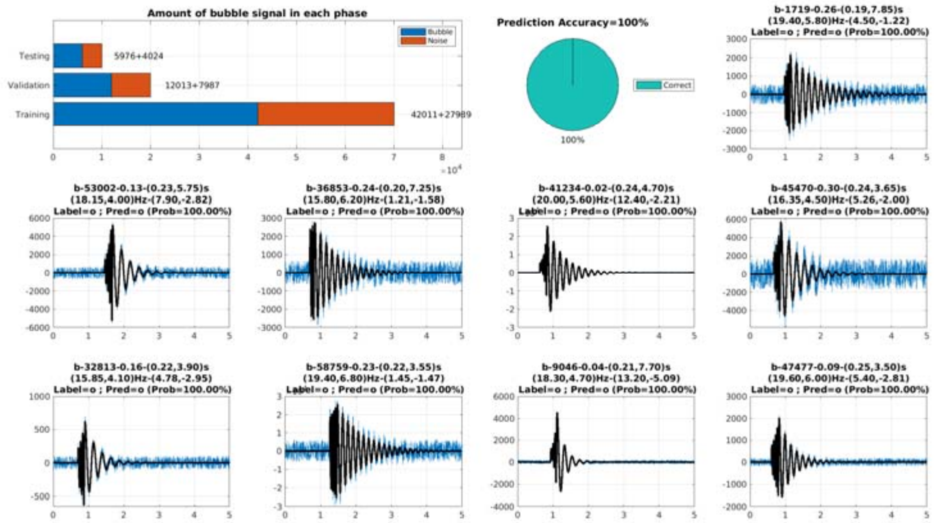

Figure 3. The examples of the synthetic waveforms (the black lines in each subplot). The varied noise levels are shown in blue.

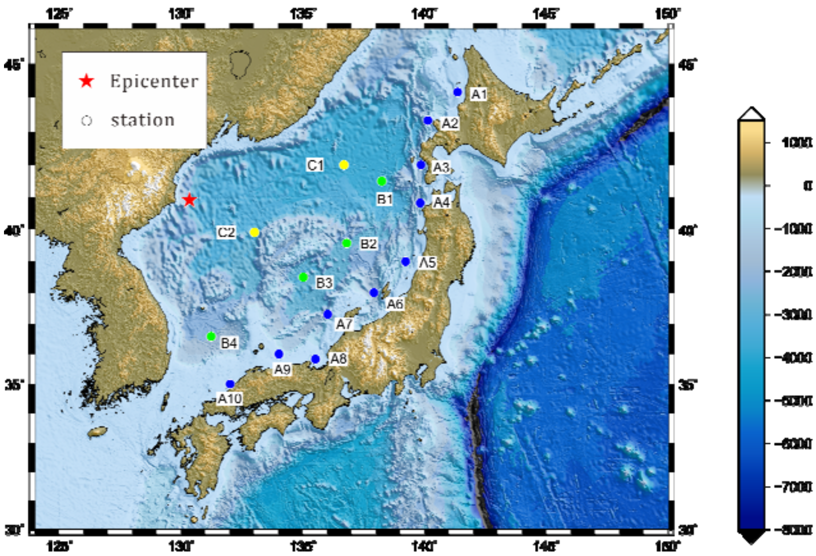

Figure 4. The targeted sites for the T-wave simulation. Three groups, indicated as A, B, and C, are designed to see the effect of geometric spreading.

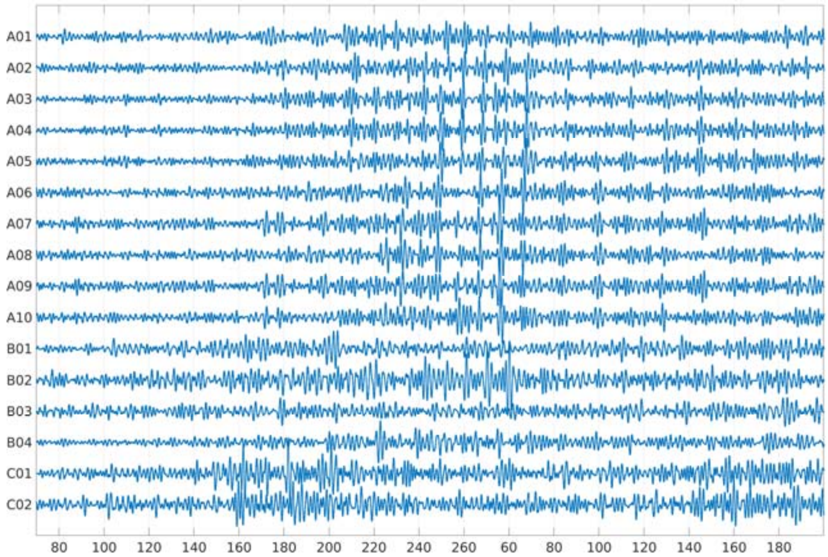

Figure 5. The simulated T waves at the targeted sites. Stations' names correspond to the indexes in Figure 4.

(4) Publications of research findings

The results of the related subjects are under arranging into journal papers.

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