ACTIVE MONITORING OF EARTHQUAKE FOCAL ZONE USING ULTRA-STABLE SEISMIC SOURCE

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ABSTRACT

The zone at approximately 30 km depth along the subducting Philippine Sea plate around Lake Hamana was possibly the pre-slip zone just before the 1944 Tonankai Earthquake (Mw=8.2). By the seismic refraction survey in the central Japan (Iidaka *et al.*, 2013) showed the presence of strong seismic reflector at this zone suggesting the presence of fluid as the cause of pre-slip. If the migration of fluid could control the earthquake generation, it is worthwhile to monitor the change of seismic reflectivity at the future focal zone for understanding of earthquake generation process.

The seismic ACROSS (Accurately-Controlled and Routinely-Operated Signal System) enables us to continuously monitor the temporal change of the amplitude and/or travel time of the reflection phases from the focal zone on the plate boundary because of very accurate-and-stable seismic signals. The seismic ACROSS source controlled by GPS clock is a fixed-type source which can generate 10-50 Hz and 40 ton-f at 50 Hz.

To evaluate the seismic characteristics before and after the change by the seismic ACROSS(s) source and optimized source-receiver array and to image the time-variant target region, we study the case with a velocity change of ~30 % in a deep slip zone with a 10-km-long and 200-m-thick at 30-km-depth, by applying an imaging method using the backpropagation of residual waveforms from the receivers. We can robustly obtain the shape and location of the time-variant targets even if it is the case of a single source or there is the change in a near-surface layer. We conclude that ACROSS technology is very promising to monitor the temporal change of physical properties in the time-variant regions with variable scale and depth.

INTRODUCTION

Any change of physical properties in an Earth's structure caused by the migration of fluid in a focal region of large earthquakes (e.g., Kasahara et al., 2001, 2003) could lead to some temporal changes in seismic waveform characteristics. We could detect those small changes by use of ultra-stable seismic source(s) and the accurately controlled seismic array.

The seismic ACROSS (Accurately-Controlled Routinely-Operated Signal System) (e.g., Kumazawa et al., 2000, Kunitomo and Kumazawa, 2004) has been introduced in Japan as the technology to monitor temporal changes of seismic properties along the seismic wave paths by using an accurately-controlled seismic source and their continuous operation.

The zone at 30 km depth along the subducting Philippine Sea plate around Lake Hamana was possibly the pre-slip zone just before the 1944 Tonankai Earthquake (Mw=8.2). The seismic refraction survey (Iidaka et al., 2013) showed the presence of strong seismic reflector at this zone suggesting the presence of fluid as the cause of pre-slip. If the migration of fluid could control tearthquake generation, it is worthwhile to monitor the change of seismic reflectivity at the future focal zone for understanding of earthquake generation process. The GPS observation of the same region showed the large aseismic deformation between 2000 and 2004 just after the Miyake-jima volcanic eruption. The total slip at the Lake Hamana could correspond to M7.2.

We have applied the seismic ACROSS technology to EOR (Enhanced Oil Recovery) and CCS (Carbon Capture and Storage) and obtained the high possibility to retrieve physical property change by simulations and field experiments in small scales (Kasahara et al., 2010a-b, 2011a-b, 2013, 2014).

In this paper, we show the numerical simulations for detecting time-variant regions, particularly the focal region along a subducting plate boundary, by a new imaging method assuming a continuous active monitoring by the ACROSS and a seismic array (Kasahara et al, 2011a).

Because seismic activities in Iran are as high as those in Japan, the seismic hazard is extremely important, in particular, the Zagros fault is the place of collision of Arabian plate and Eurasian plate. In addition, the subduction zone earthquake (Mw=8.1) occurred in Makran region at the border of Iran and Pakistan in 1945 (e.g., Quittmeyer.1979). This region is also important to study.

BACKGROUND OF ACTIVE MONITORING BY SEISMIC ACROSS

The seismic ACROSS source we use is the rotational source to obtain ultra-stable source signatures (Fig. 1). The rotation of mass is controlled adjusting to the GPS time base. The ACROSS source can generate 10-50 Hz vibration with 40 ton-f at 50 Hz, nearly equivalent to the force by the Vibroseis. The force of seismic ACROSS is given by rotation of eccentric mass. The force F is given by F=Mω2,

where M is mass and ω is angular frequency.

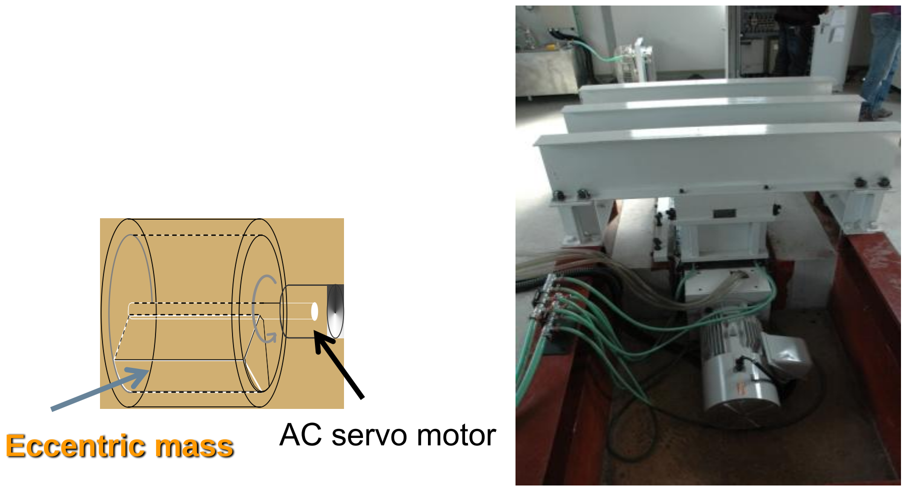

Figure 1. Seismic ACROSS source. The rotational axis of motor is horizontal. By the combination of clockwise and anticlockwise rotations, we can sythesize vertical and hirozontal signle forces, respectively.

The ACROSS source uses frequency sweep similar to Vibroseis, but the operation of source and processing method are different from ordinary seismic reflection technology. If the sweep duration is To, the data give a set of line spectra with spacing of 1/To in frequency domain. By the division of observed seismic records by the source signature in frequency domain, the transfer function between the source and each receiver is obtained. Switching the rotational direction, it can generate single force perpendicular to the rotational axis such as vertical and/or horizonal vibations.

We can stack the data only on the known line spectra to enhance the S/N (Fig. 2). For this case shown in Fig. 2, the seismic wave arrivals traveling down to 20 km depth were obtained at 61.2 km distance by the stacking of a week-long data.

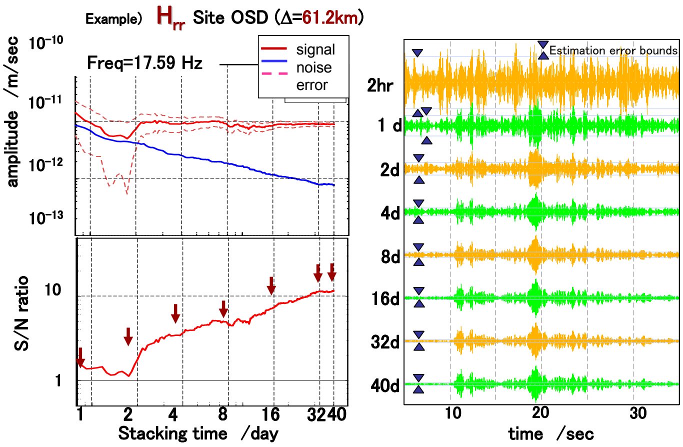

Figure 2. An example of improvement of S/N by staking at 61.2 km distance using the seismic ACROSS (Kasahara *et al*, 2010). (Left): Change of S/N by the length of stacking.
(Right): Waveform change by increaseing of staking duration, from 2 hours (top) to 40 days (bottom).

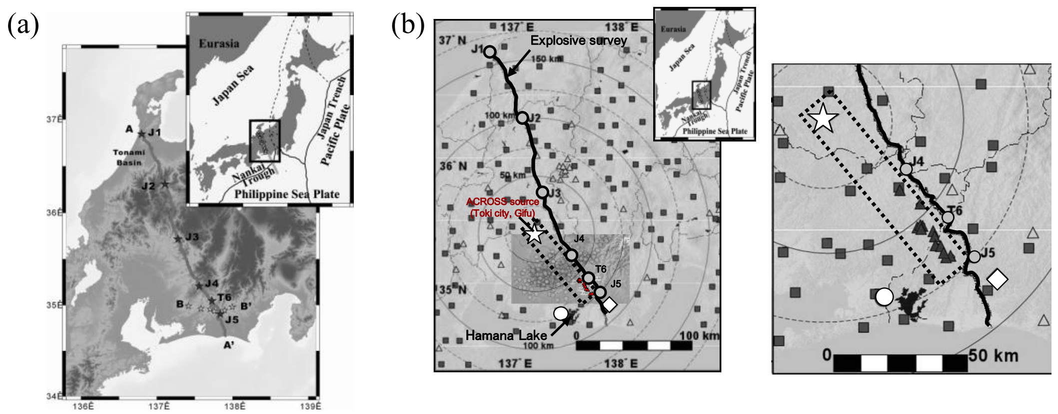

Figure 3. (a) Seismic survey line and location of chemical explosions for the controlled source seismic survey in the NNW-SSE direction in the central Japan (modified after Iidaka *et al*., 2003).
(b) Loation of ACROSS feasibility study in 2004-2005. The ACROSS is shown by star and the zone of dotted line is the temporal sesimic obseration (Kasahara *et al*, 2010).

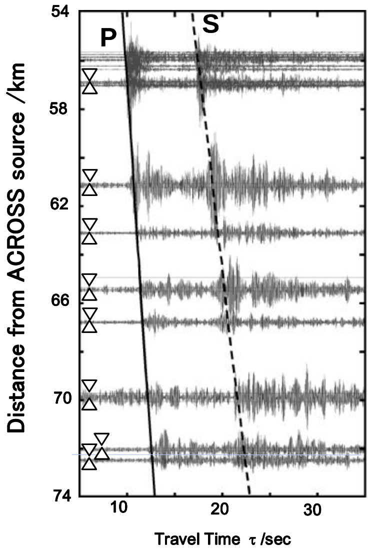

Figure 4. Transfer function Hrr (radial force and radial comonent) in the time domain for all stations from 54 to 74 km offset distances with a stacking period of 40 days. Source loaction was shown in Fig. 3b. The thin solid and dotted lines represent the theoretical travel times of refracted P- and S-waves, respectively. Several seismic phases have amplitudes greater than the noise levels (after Tsuruga *et al.*, 2005).

A part of results obtained by the former feasibity study above the Philipine Sea plate subductinon zone (Tsuruga et al, 2005, Kasahara et al., 2010) is shown in Fig. 4. As seen in this figure, we can identify the P and S arrivals up to 75 km by the stacking 40-days-long dataset excited by the ACROSS source. However, we cannot identify PxP and SxS arrivals reflected at the Philippine Sea plate because the distance of observation was not long enough.

NUMERICAL SIMULATION

To investigate the optimal source and receiver array to detect the temporal change of PxP reflected at the Philippine Sea plate and examine the imaging of future focal zone, we carried out numerical simulation by the method proposed by Kasahara et al. (2011a). The followings are the basic steps of simulation and imaging analysis.

1) Prepare 2-D structural models (i.e., models of velocities VP and VS, attenuation QP and QS, density) including a time-variant target region. We made simulation for the case of a deep large-scale subduction-zone model including a time-variant non-slip zone.

2) Simulate the vertical and horizontal seismograms by a FDM (Larsen et al., 1995) assuming a single-force source of 4-Hz zero-phase Ricker wavelet and plural seismometers at the surface. We also identify the major seismic phases on the seismograms referring to the theoretical travel times calculated by ray theory.

3) Calculate the differences of waveforms between seismograms before and after the change.

4) Apply the imaging method to the differences of waveforms by using finite-difference back-propagation technique (Kasahara et al., 2011a). On the base of the reciprocity theorem, we apply vertical and horizontal forces at each receiverۥs location and finally calculated total energy, P- and S-wave potentials for all grid points.

We here described about the subducting plate model as a larger-scale time-variant region model. The results are shown in Figs. 5 and 6. Fig. 6a shows the 2-D velocity model across the central Japan (Tsuruga et al., 2005) assuming a time-variant slip zone with a velocity change of ~30 % (e.g., VP=3.5 to 2.5 km/s) in a 10-km wide and 200-m thickness zone at 30-km depth along the Philippine Sea plate in Japan denoted by a red rectangular.

A part of results was reported by Tsuruga et al. (2011).

RESULTS OF SIMULATION

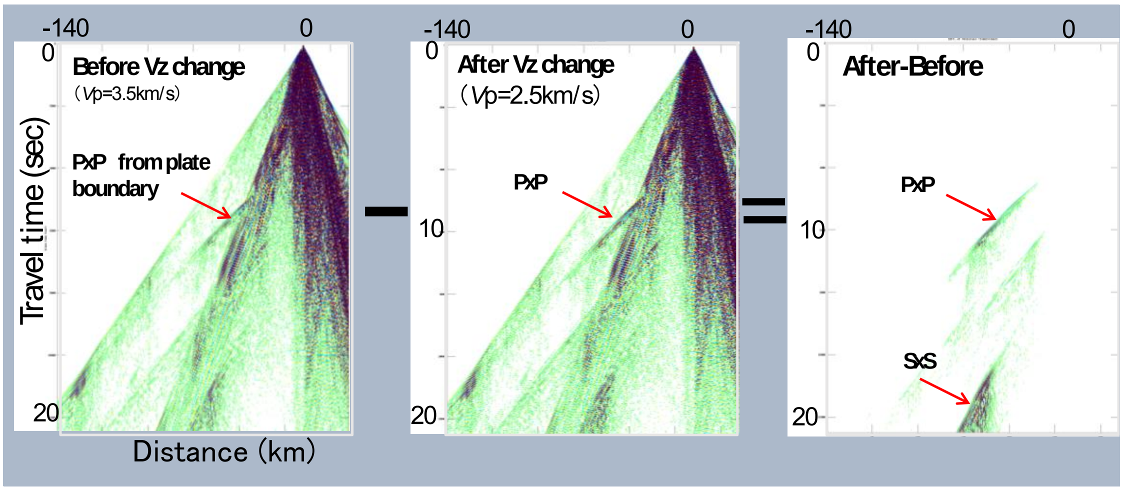

Figure 5. The source بA پgather records of before, after and residuals of velocity change.
The residuals show clear PxP and SxS arrivals.

We calculated the transfer functions before and after and residual shown in Fig. 5. Remarkable reflection phases PxP and SxS reflected from the target zone reveal at the offset distances of 25 to 60 km from the source-A and 70 to 80 km from the source-B.

The result of backpropagation of the residuals is shown in Fig. 6. In both cases for the sources-A and B, we found that the target region is clearly identified by the remarkable reflection phase.

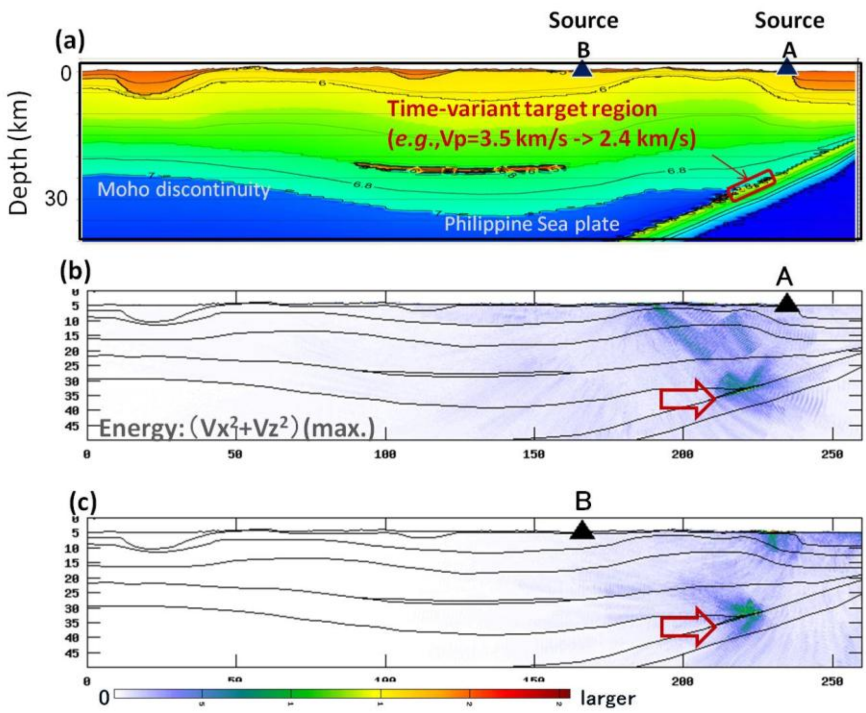

Figure 6. (a) A 2-D seismic velocity structure model for the central Japan (Tsuruga *et al.*, 2005). Diagrams (b) and (c) show the summary of time-slices evaluated from the ranged dataset for each of the sources A and B.
In both cases, the time-variant target region is clearly indicated (after Tsuruga *et al.,* 2011).

DISCUSON AND CONCLUSIONS

The area of Lake Hamana is supposed as the pre-slip region for the gigantic earthquake generation along the subducting Philippine Sea plate. The former feasibility study using ultra-stable seismic ACROSS source shows that the use of ACROSS for the active monitoring is possible by the stacking of a week to month long dataset. However, the observation cannot tell the place of time-variant zone due to insufficient offset distance.

In order to locate the time-variant zone, we carried a numerical simulation assuming single seismic source and a seismometer array. The both cases of seismic sources A and B showed the retrieval of time-variant zone if we assume the enough velocity change due to the migration of fluid to the subduction boundary.

If fluid migration to the future focal zone triggers any gigantic earthquakes such as the 2011 Tohoku Earthquakes (Mw=9.0), the 1944 Tonakai Earthquake (Mw=8.2), the 1946 Nankai Earthquake (Mw=8.4) , the 1995 Hanshin-Awaji Earthquake (Mw=7.3), the 1946 Makran Earthquake (Mw=8.1) and etc. along plate boundaries, the present approach could monitor the reflectivity change at plate boundaries.

The above results suggest the continuous seismic monitoring of time-variant zone by a few seismic sources and a seismic array is promising for as the oil and gas field scale as gigantic earthquake monitoring scale.

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