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PS Repeatability Evaluation of Time-Lapse Technology Using Ultra-Stable Seismic Source*

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Abstract

For the seismic time-lapse studies, we have used Accurately Controlled and Routinely Operated Signal System (ACROSS) with an ultra-stable seismic source to monitor the change continuously. To discuss the true temporal change of the subsurface, it is necessary to evaluate the repeatability of the measurement system. Kragh and Christie (2002) proposed the normalized root mean square (NRMS) repeatability of the time-lapse measurements.

In order to clarify the repeatability of our time-lapse study using ACROSS, we examined the data obtained in Al Wasse Field in Saudi Arabia. In the source-gather seismic records using the ACROSS seismic source, the first arrivals decayed at the offset distance further than 700 m. This is thought to be caused by the presence of velocity inversion just below the top layer. We calculated NRMSs of the first arrivals at the stations within 700 m from the source.

We found that the NRMS repeatability in the ACROSS source room was less than 2% for a 12 days period. The NRMS variations of two stations among 31 were smaller than 5% during two months in 2012-2013 and 2015. Considering the NRMS at the source room, the NRMS of source itself is small (~less than 2%) and the environmental changes such as water pumping and temperature change affect the NRMSs of the field stations. The NRMSs of the other stations show very large variation. This is probably not due to the source signature change, because the geophones were located at the ground surface and the test field has more than 64 water-pumping stations. The water-pumping stations pump up

water from the aquifer at ~400 m depth and it affected the seismic records. The presence of aquifer and weak P-wave first arrivals could degrade the NRMS estimation.

The NRMSs obtained by the source-room geophone and two field stations showed the greatest repeatability of the measurement system with ACROSS for at least two months. The excellent repeatability of our seismic monitoring technology could accelerate the use of the time-lapse technique in the unconventional oil and gas exploration and productions.

Introduction

To monitor the temporal changes of the subsurface structure, time-lapse technology is essential technique. Some useful applications of the time-lapse technology are EOR for heavy oil, exploration and production of shale gas, and monitoring of injected CO_2 in CCS (carbon capture and storage). For the time-lapse studies, we have used the ACROSS (Accurately Controlled and Routinely Operated Signal System) methodology to monitor the change continuously using precisely controlled signal system (Kasahara et al., 2010; Kasahara and Hasada, 2016). The ACROSS seismic source is shown in Figure 1.

In order to discuss the true subsurface change using the time-lapse data, it is necessary to clarify the repeatability of the measurement system including instrumental parts of seismic source and receivers. We think that many factors contribute to repeatability of the observation; seismic source signature change, ground coupling of source and/or receivers, fixing accuracy of source and/or receiver locations, media along paths, and true subsurface changes (Kasahara and Hasada, 2016).

Seismic Data Obtained in Saudi Arabia and Their Characteristics

To examine the repeatability of the time-lapse study using ACROSS seismic system, we used data obtained at 31 seismic stations in the Al Wasse Field, Saudi Arabia in 2013-2014 and 2015 (Figure 2). Because each arrival travels its own path, it is necessary to know the nature of each phase.

We examined the source-gather seismic records shown in Figure 3a acquired by the refraction survey using the ACROSS source and the 50-m-spacing temporary geophone array. As seen in this record section, the first arrivals decayed at the offset distance further than 700 m. There is a low velocity layer associated with the aquifer below 100 m and the basement is at ~900 m (Figure 3b). The deeper arrivals appear at a distance further than 1.5 km with the apparent velocity of Vp = 4.5 km/s. The characteristics of weak first arrivals at the distance around 500-700 m might affect the repeatability.

NRMS Repeatability

Kragh and Christie (2002) proposed NRMS for the repeatability.

$$NRMS = \frac{200 \times RMS(a_t - b_t)}{RMS(a_t) + RMS(b_t)}, \qquad (1)$$

where the *RMS* operator is defined as:

$$RMS(x_i) = \sqrt{\frac{\sum_{t_1}^{t_2} (x_t)^2}{N}}. \qquad (2)$$

N is the number of samples in the interval t_1–t_2. If both traces are uncorrelated, the NRMS error is 200%. If one of the traces has half the amplitude of the other, the NRMS is 66.7%. In the case of the Gulf of Mexico, the best values were 18-30% (Kragh and Christie, 2002). Eiken et al. (2003) obtained approximately 40% NRMS by two surveys with 25 m lateral offset. For most of 4D survey, 10-30% is thought to be a typical good value (Johnston, 2013).

Results of Repeatability Estimation

We calculated the travel-time variation (dT) and the amplitude variation (dA) (Figure 4 and Figure 5) using the cross-correlation analysis of the P-wave portions. The dT and the dA in the station #53 shows small temporal variation during two separated periods (Figure 4). There are two years between the first and the second periods. The dT variation of #53 in the first period was less than ±0.5 ms (Figure 4). The dT and dA for 8 stations are shown in Figure 5. The lowest variation set is thought to be the true characteristics of the source itself.

We examined the NRMS repeatability based on equation (1) using a geophone in the ACROSS source room (Figure 6). Although the analyzed duration is short, the NRMS during 12 days were less than 2%. We can clearly identify daily variations from Figure 6. Because the room temperature was kept constant, the cause of daily variation could be housing deformation due to the large temperature variation of outside air. The ACROSS seismic source was in the desert area in winter and the outside temperature was very low during night time.

To obtain repeatability of the stations outside the source room, we calculated NRMS (Eq. 1) in the following way: (1) 2-hours transfer functions after weighted stack for sliding 1-day window are calculated for the stations within 1000 m from the source, (2) The time window of 50% cosine taper at ±25 ms around the presumed P-wave arrival times tp = x / 3500 are applied, (3) The NRMSs are calculated with the reference traces 2012/12/30 0:00 and 2015/4/19 0:00 for the first (2012–2013) and the second (2015) periods, respectively, then (4) 1 day median was applied. Because of the different source signatures in 2012-2013 and 2015, we calculated the NRMS using the different reference date. The frequency range in the first period was 10-50 Hz and one in the second period was 10-40 Hz.

The NRMS variation of stations #33 (Figure 7a) and #53 (Figure 7b) were smaller than 5% in the first and the second periods, and it is similar results seen in dT and dA. Considering the NRMS at the ACROSS source room, the NRMS of source itself is small (~less than 2%) and the environmental change such as pumping and temperature change affect the NRMSs of the grid stations. The NRMSs of the other stations show very large variation probably not due to the source signature change. Because the geophones were located at the ground surface and the test field has more than 64 water-pumping stations, the apparent NRMSs observed at the grid stations show great temporal variation. However, the temporal variations are time lapse itself.

Discussion and Conclusion

In the time-lapse studies, many factors could contribute to the repeatability of observation: seismic source signature change, ground coupling of source and/or receivers, fixing accuracy of source and/or receiver locations, media along paths, and true subsurface changes (Kasahara and Hasada, 2016). Among these possible factors, the source signature repeatability is one of the most important factors. To obtain excellent source repeatability, the ground coupling of the source should be kept the same. The source signature of conventional vibration sources tends to vary for each vibration. If the repeatability of the source is low, appropriate compensation of the source signature is needed.

The ACROSS test field in Saudi Arabia is located in the area of the water-pumping stations to pump water from more than 64 wells. The aquifer at ~400 m depth could affect the seismic records. According to the refraction survey, the P-wave first arrivals quickly decay with distance and disappear around 700 m due to the presence of a low velocity layer. The presence of aquifer and weak P-wave first arrivals could affect the NRMS estimation.

The source room geophone showed less than 2% NRMS during 12 days. The NRMS of two stations among 31 grid stations were less than 5% during 1-2 months. The dT and dA of these two stations are extremely small, such as 0.2 ms during 1-2 months with the interval of 2 years. The NRMS, dT and dA of the other stations were large, suggesting the effects of weak P-wave arrivals and water pumping.

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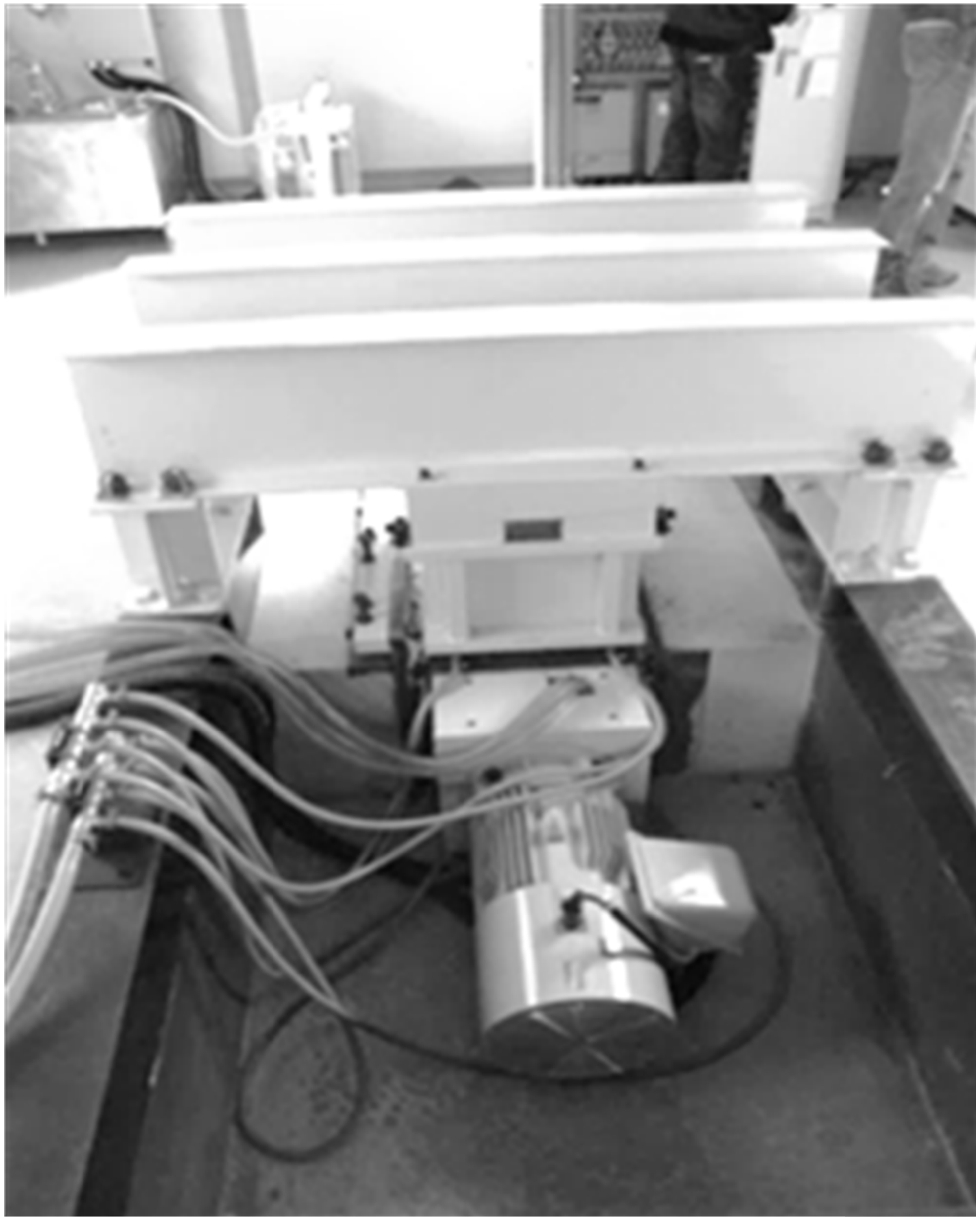

Figure 1. The ACROSS seismic source used in Saudi Arabia (Kasahara and Hasada, 2016). The electric servomotor rotates an eccentric weight around its rotational axis. Vibration from 10 Hz to 50 Hz with 3.9×10^5 N (40 ton f) at 50 Hz can be generated. The rotational speed is precisely controlled by the time base given by a Global Positioning System (GPS).

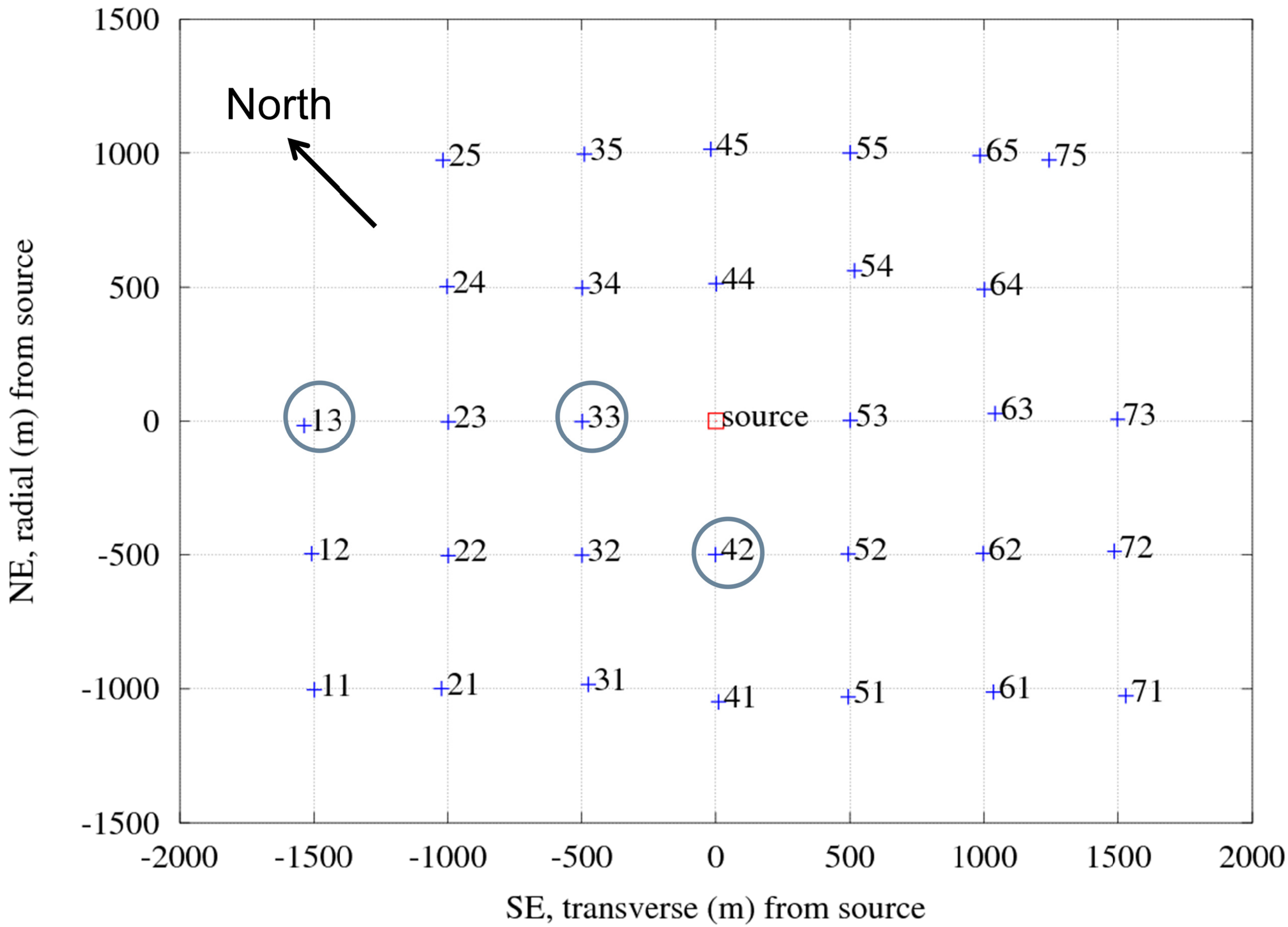

Figure 2. Map of geophones on grids in Al Wasse Field in Saudi Arabia.

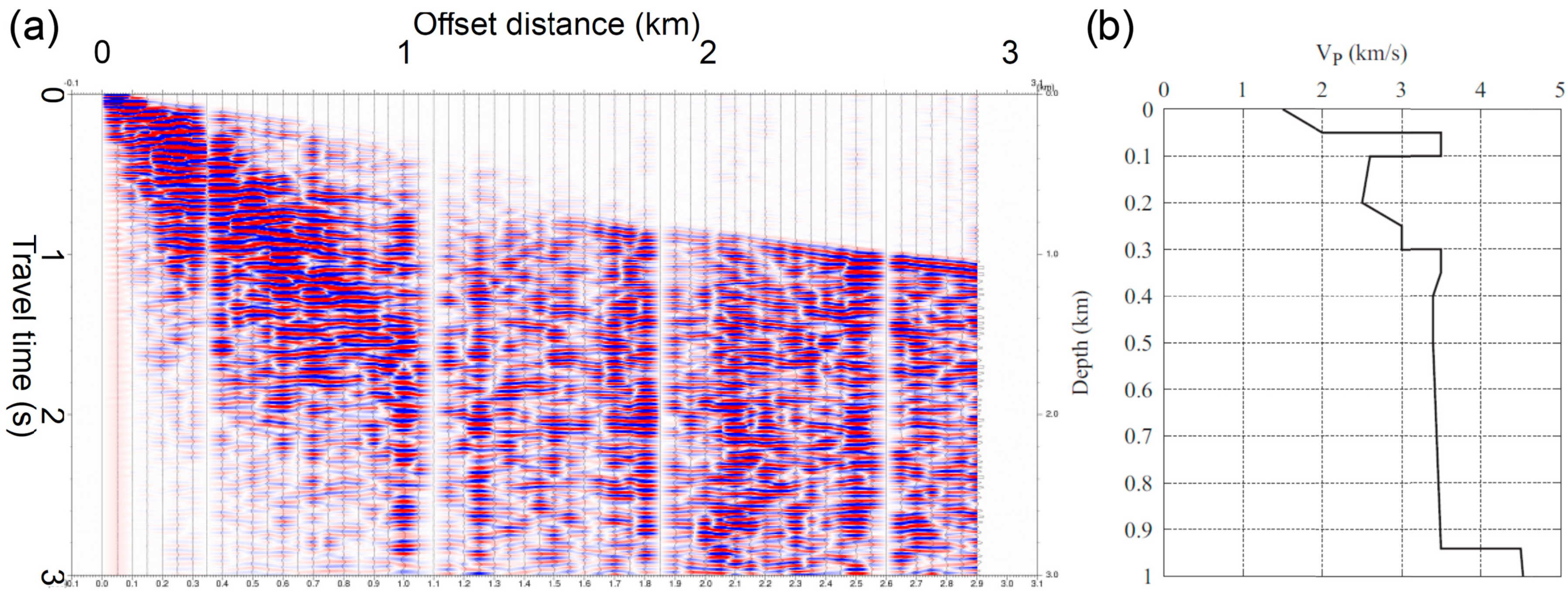

Figure 3. (a) Seismic source-gather records of vertical force received by a 50-m-spacing vertical geophone array. The vertical axis is travel time and the horizontal axis is distance. Two hours of data were used. (b) The velocity structure model estimated by the refraction survey using the ACROSS source (Kasahara and Hasada, 2016).

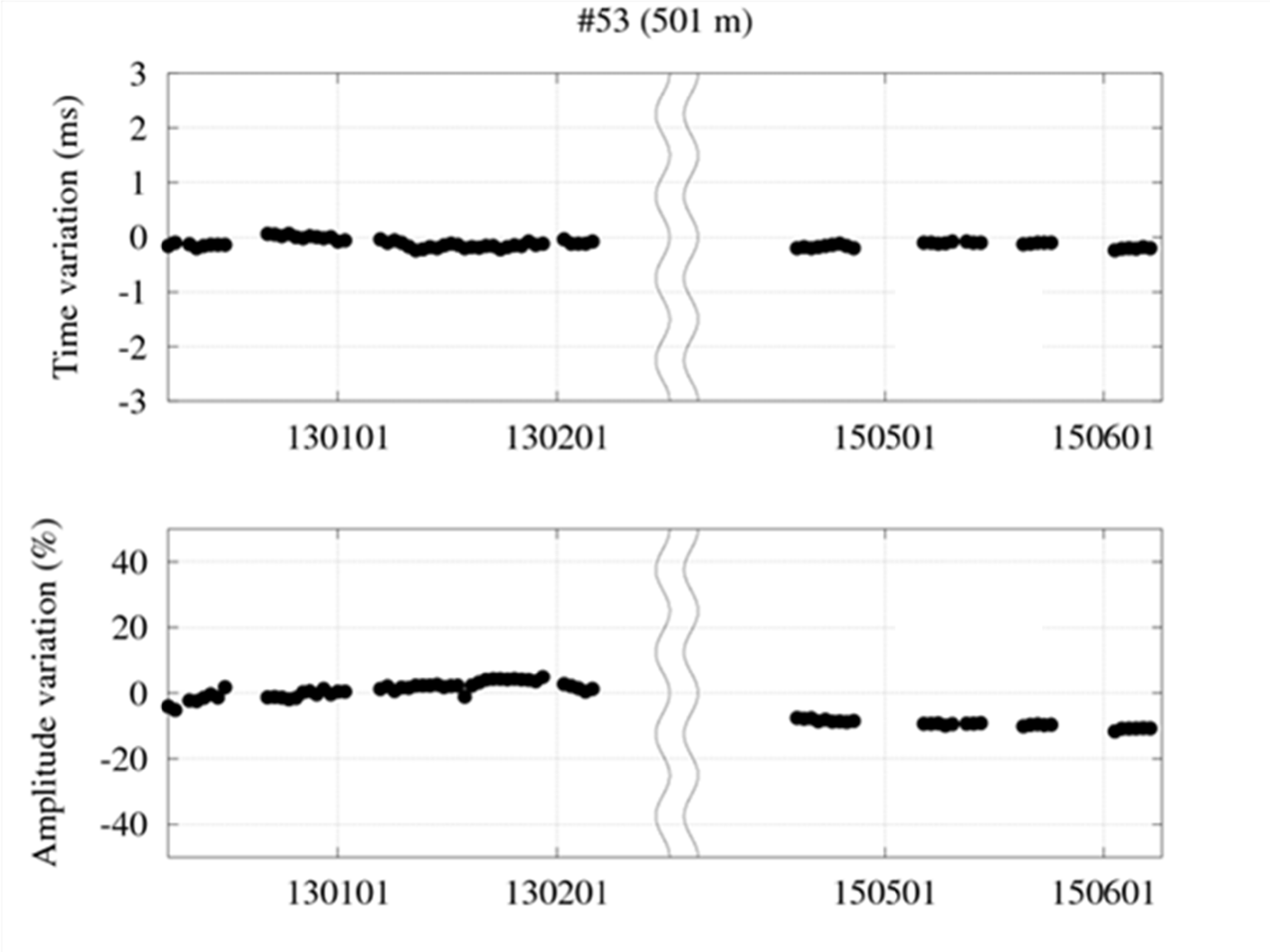

Figure 4. Daily variation of dT and dA of P-phase using cross-correlation at the station #53 (the offset distance is 501 m). The dT variation in the first period was less than ±0.2 ms. The dA variation was within a few percent in the first period and less than 10% in the second period.

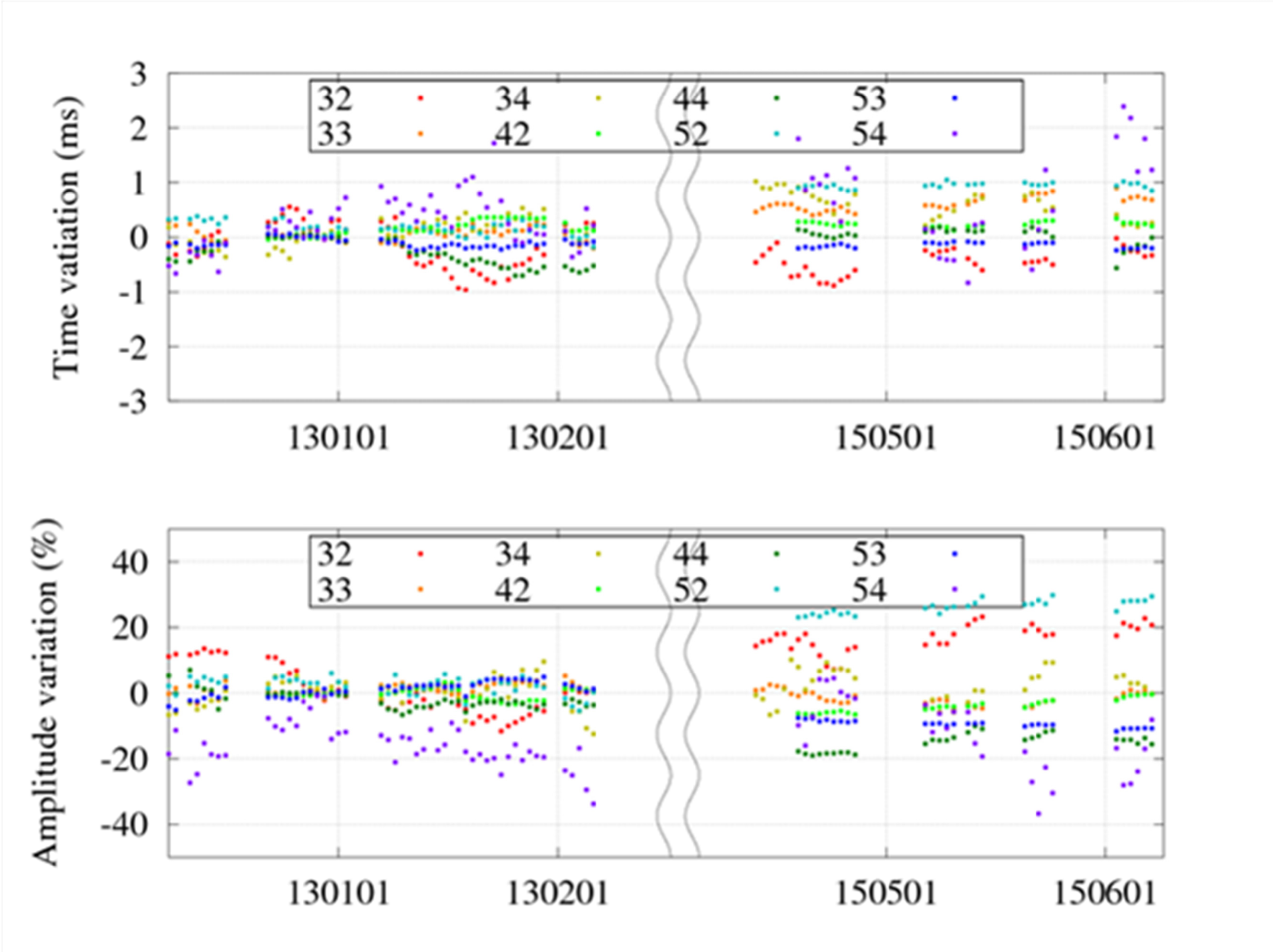

Figure 5. dT and dA variations of 8 stations. The offset distances are from 500 to 750 m. Some stations show extremely small temporal changes and the others have large changes due to weakness of P arrivals and subsurface changes induced by water flow in the aquifer.

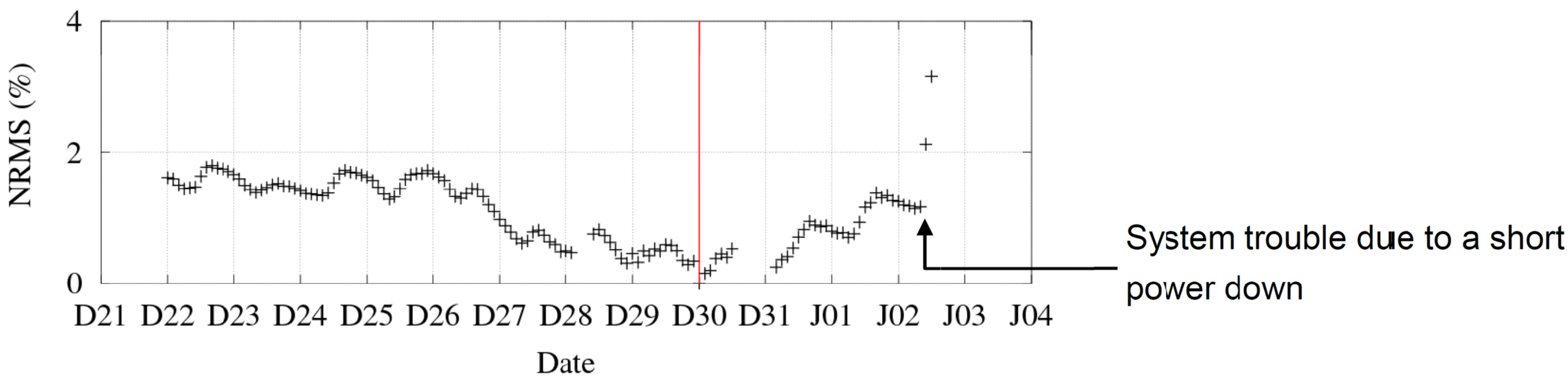

Figure 6. NRMS using a geophone in the ACROSS source room from December 22th, 2012 to January 2nd, 2013. The reference date is December 30th. Clear daily variation was observed. The NRMS is less than 2% during this period.

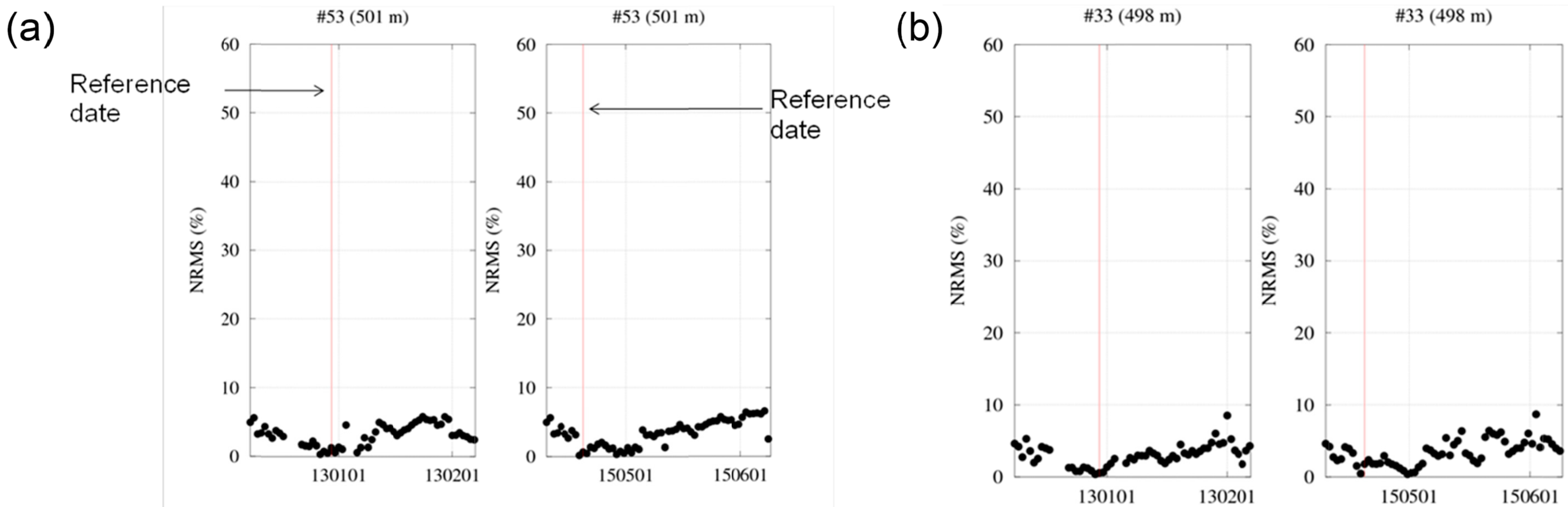

Figure 7. (a) NRMS variation of #33. The reference dates are December 30th, 2012 and April 19th, 2015. The NRMS is approximately less than 5% during one to two months. (b) NRMS variation of #53. The reference dates are December 30th, 2012 and April 19th, 2015. The NRMS is slightly greater than 5% during one to two months.