Proximity AE Doublets Analysis for Subsurface Fracture Measurement

Koji Nagano, Department of Computer Science and Systems Engineering,
Muroran Institute of Technology,
Muroran, Hokkaido, 050-8585, Japan, email: nagano@csse.muroran-it.ac.jp

Abstract: Proximity Acoustic Emission (AE) doublets analysis is used for subsurface fracture measurement. AE is a microseismic event. Location and shape of subsurface fracture is estimated from distribution of AE sources. Measurement of subsurface fracture is important in many areas of human activities associating with the Earth. Motion of subsurface fracture causes earthquakes. Geothermal energy is extracted from subsurface fracture reservoirs in which steam and hot water are stored. Carbon dioxide is also stored in tiny spaces of subsurface fracture.

Proximity AE doublet analysis is a new method in which fine structures of subsurface fracture can be estimated. Proximity AE doublets have a similar waveform, and they occur in a succession with an interval that is less than 1 s. Accurate relative location between AE sources can be realized because a medium, in which AE waves propagate, does not change during the interval. Intervals of P-wave and S-wave between proximity AE doublets are detected in cepstrum analysis. Proximity AE doublets have one or two peaks at their intervals in their cepstrum. In my analysis I also show relative locations between AE sources of proximity AE doublets.

Keywords: Acoustic Emission, micro seismic event, proximity AE doublets, source location, subsurface fracture

1. Introduction

Geothermal energy is important renewable energy. Energy efficiency of a geothermal power plant is good. A geothermal power plant produces less CO_2. Furthermore, it supplies its power more constantly and has higher generating power than other renewable energy sources, wind and solar. Use of geothermal energy is, however, restricted because estimation of a subsurface reservoir is difficult.

Geothermal energy is stored as steam or hot water in tiny spaces in subsurface fractures. Figure 1 shows a concept of geothermal energy extraction. We drill a borehole into a subsurface fracture. Hydraulic injection is used to extend a subsurface fracture. It is important and necessary to measure a subsurface fracture so that we can get geothermal energy from the subsurface reservoir.

Acoustic Emission (AE) technique is used to measure subsurface fractures. AE events are microseismic events. When a subsurface fracture is stimulated using water injection, the fracture moves and there are AE events. We can estimate location and shape of the subsurface fracture by analyzing the AE events.

Analysis of AE doublets/multiplets is a seismological tool to investigate the subsurface structure [*Poupinet et al. 1984*]. AE doublets/multiplets have similar waveforms. AE events with similar waveforms occur in the same or proximal fractures and share a similar source mechanism.

Analysis of AE doublets/multiplets has provided highly precise relative location between similar events. Analysis of AE doublets/multiplets have demarcated the detailed structure of a fracture reservoir in a geothermal field. *Phillips* [2000] studied microseismic events induced by hydraulic stimulation of a hot-dry-rock geothermal reservoir in the Rhine Graben near Soultz-sous-Forêts,

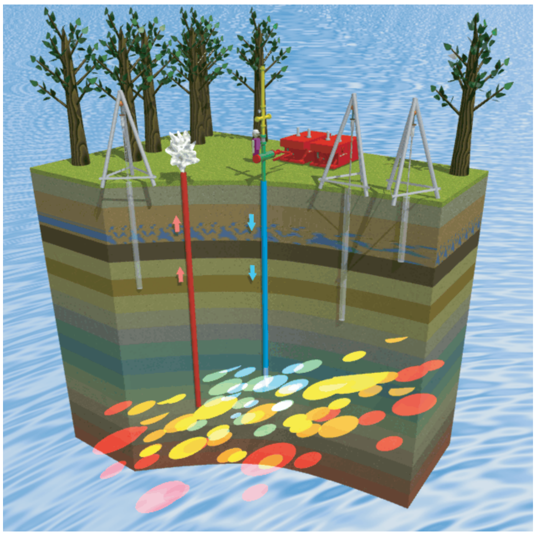

Figure 1: Geothermal energy extraction system.

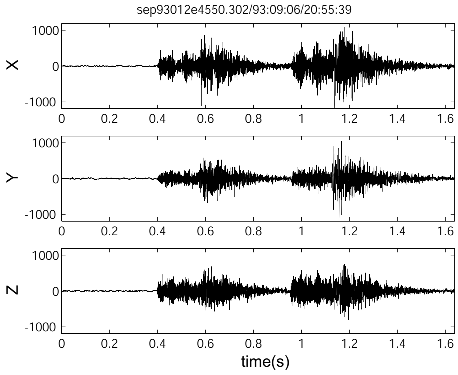

Figure 2: Proximity AE doublets.

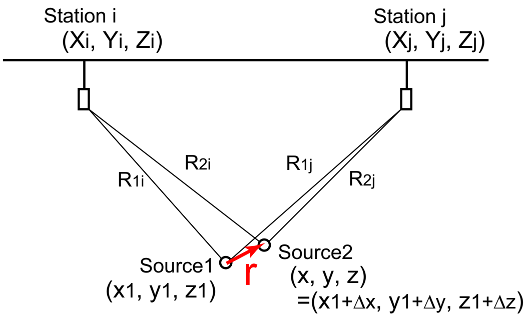

Figure 3: Relative distance between AE sources.

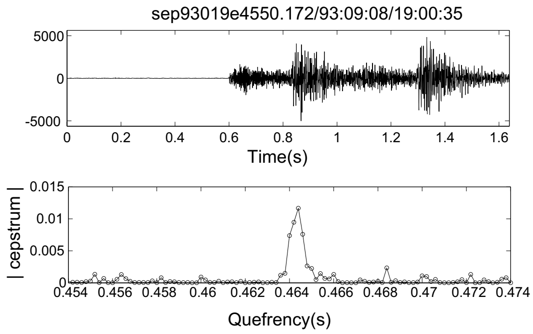

Figure 4: Proximity AE doublets and their cepstrum.

France. He relocated the events with similar waveforms. His study of the location of the micro-seismic events helps delineate the fracture network and the stress fields that govern the flow of fluids. *Moriya et al.* [2002] revealed fracture orientations in the Soultz-sous-Forêts HDR field by showing relative hypocenters among similar microseismic events. A combination of the relative hypocenters of three or more similar events reveals the fracture orientations. They also described that the estimated orientations of the fractures were consistent with those of a tectonic stress field.

2. Proximity AE Doublets and Relative Source Location

AE doublets are recorded in a single data file when the interval between the events is much shorter than the data length. Similar events overlap each other and are recorded as one wavelet when the second event arrives before attenuation of the first event. An example of such AE events is shown in Figure 2. Two events with similar waveforms are visible in the data file. The second event arrives in the attenuating process of the first event. These AE doublets are called proximity AE doublets in this paper.

Analysis of proximity AE doublets provides a more accurate relative location between the AE sources than conventional analysis of the AE doublets/multiplets does. Relative location shown in Figure 3 can be estimated by analyzing intervals between the AE doublets in several stations. Temporal subsurface changes are neglected in this analysis. It is, however, difficult to estimate the interval directly in its time domain analysis.

I use cepstrum analysis to estimate the interval between proximity AE doublets. Cepstrum analysis is the inverse Fourier transform of the logarithm of a signal's power spectrum [*Oppenheim and Schafer*, 1975]. Cepstrum of the proximity AE doublets exhibits a peak at interval as shown in Figure 4.

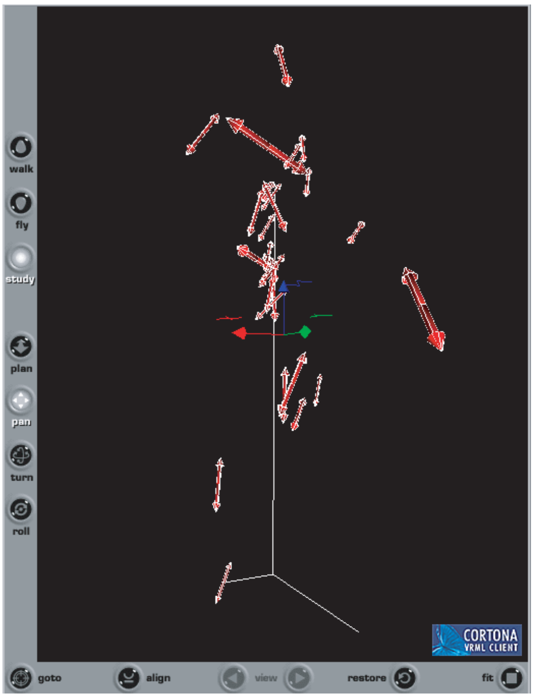

Figure 5: Relative locations of proximity AE doublets

Cepstrum analysis can provide two important pieces of information for analysis of proximity AE doublets. Estimation of waveform similarity is necessary to discriminate proximity AE doublets from overlapping independent events. The interval between the similar events is estimated when the waveform represents the proximity similar events. The similarity of waveforms and the interval between the similar events can be estimated simultaneously in cepstrum analysis without any assumptions.

The interval between proximity AE doublets is estimated using cepstrum analysis. The proximity AE doublets have a line cepstrum whose quefrency represents the interval. Width of the peak in the cepstrum is absolute value of difference between intervals of P-waves and S-waves in proximity AE doublets. Relative location between AE sources can be calculated from the width of the peak in the cepstrum, as shown in Figure 4. The relative location $(\Delta x, \Delta y, \Delta z)$, shown in Figure 3, is a function of distance R_{2i} between a source of the second AE event and station i. The distance R_{2i} is calculated from the width of the peak,

$$|\Delta T_{Pi} - \Delta T_{Si}| = \begin{cases} (R_{1i} - R_{2i})\left(\frac{V_P - V_S}{V_P V_S}\right) & (R_{1i} > R_{2i}) \\ (R_{2i} - R_{1i})\left(\frac{V_P - V_S}{V_P V_S}\right) & (R_{2i} > R_{1i}) \end{cases} \quad (1)$$

where R_{mi} is distance between AE source m and station i, ΔT_{Pi} and ΔT_{Si} are intervals of P-wave and S-wave between proximity AE doublets in station i, respectively. V_P and V_S are velocities of P- and S-waves. Figure 5 shows results of relative locations that are estimated in proximity AE doublets analysis. The AE data in Figure 5 were measured in Soultz geothermal field during hydraulic fracturing in 1993 [*Moriya et al. 2002*].

3. Discussion

Proximity AE doublets have not been analyzed in conventional analysis of AE doublets /multiplets. The cepstrum analysis shows good results for analysis of proximity AE doublets. Therefore, the cepstrum analysis of proximity AE doublets increases the number of AE doublets/multiplets. The more AE doublets/multiplets are analyzed, the more information regarding fracture is obtainable. The relative location estimated in proximity AE doublets analysis will reveal more fine structure of fracture reservoirs.

One advantage of the AE doublets/multiplets analysis is that their sources are related to each other because their waveforms are similar. This advantage improves accuracy of relative source location and aids in solving a source mechanism. It is difficult to relate sources of independent seismic events. Analysis of proximity AE doublets can provide more accurate relative location because velocity of media in which AE events propagate does not change.

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