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Identification of similar seismic events using a phase-only correlation technique

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HIGHLIGHTS

- A method for identification and clustering of similar AE events is developed.
- The method uses phase-only correlation and cluster analysis.
- The resulting tree shows the degree of linkage among similar events.

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ABSTRACT

Identification and clustering of similar acoustic emission (AE) events are important to determine source locations precisely and to evaluate subsurface cracks. An AE cluster analysis method using phase-only correlation (POC) is proposed to identify and hierarchically classify similar AE waveforms. The POC of time-varying spectral representations is used to evaluate the similarity between two waveform images in the time–frequency domain, and cluster analysis is used to classify the waveforms into groups according to a distance measure. The method is applied to waveforms from local earthquakes in Japan to assess its ability to identify similar waveforms perturbed by white noise.

1. Introduction

Evaluation of subsurface cracks is important in, for example, the monitoring of mining processes and the design of borehole drilling targets for geothermal energy extraction. Acoustic emissions (AEs) can be used to estimate the locations of cracks, which are fluid flow paths in a geothermal reservoir, and also to evaluate damage to a rock mass [1–4]. AE events with similar waveforms generally represent repeating events on the same crack surface. Cross-spectrum analysis and cross-correlation methods can be used to identify similar AE events, determine precise AE source locations, and identify the orientations of crack planes as well as their locations [1,3–5]. For instance, the precise source location of AE events induced on a geological fault by stress changes during mining indicated that repeated energy releases were occurring at an asperity on the fault.

Usually, large numbers of events should be grouped to improve source location accuracy, because many travel-time delay data from similar AE events can constrain relative source locations. However, it is often difficult to classify AE waveforms into appropriate groups. Therefore, an objective method for grouping AE waveforms and identifying similar events is needed.

Cross-correlation functions are often used to identify similar AE waveforms from AE events [6]. However, it is difficult to analyze and classify noisy waveforms by using the degree of similarity, because optimal values are needed for parameters such as the time-window length for the calculation and the frequency resolution for the spectral estimation. The appropriate grouping of AE events is important because the detection accuracy of time delays between two AE waveforms depends on the degree of cross-correlation between them.

Phase-only correlation (POC), which is used in electronics and communication engineering for matching images such as fingerprints, is a simple, robust technique for evaluating the similarity of two images [7–9]. The POC method deals well with noise and perturbations superimposed on the signals [9], and it has great potential for use in geophysical exploration, including for the identification of similar AE events. In this paper, the application of a technique based on POC to evaluate and classify the waveform similarity of AE events is described.

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2. Method

The POC method is a pattern recognition technique that has been developed for matching images such as those of fingerprints. The POC function F_h is defined by the following equations [9]:

$$F_h(k_1,k_2) = \sum_{n_1=-M_1}^{M_1}\sum_{n_2=-M_2}^{M_2} f_h(n_1,n_2)W_{N_1}^{k_1n_1}W_{N_2}^{k_2n_2} = A_h(k_1,k_2)e^{j\theta_h(k_1,k_2)} \quad (1)$$

where $k_1 = -M_1,\ldots,M_1$, $k_2 = -M_2,\ldots,M_2$, $W_{N_1} = e^{-j\frac{2\pi}{N_1}}$, and $W_{N_2} = e^{-j\frac{2\pi}{N_2}}$. $A_h(k_1,k_2)$ denotes the amplitudes of $F_h(k_1,k_2)$, and $e^{j\theta_h(k_1,k_2)}$ is their phase. Then, the function $\widehat{R}_{h\ell}(k_1,k_2)$ can be defined as

$$\widehat{R}_{h\ell}(k_1,k_2) = \frac{F_h(k_1,k_2)\bar{F}_\ell(k_1,k_2)}{|F_h(k_1,k_2)\bar{F}_\ell(k_1,k_2)|} = e^{j\theta(k_1,k_2)} \quad (2)$$

where $\bar{F}_\ell(k_1,k_2)$ is the complex conjugate of $F_h(k_1,k_2)$ and $\theta(k_1,k_2) = \theta_h(k_1,k_2) - \theta_\ell(k_1,k_2)$. The POC function can then be represented as the inverse discrete Fourier transform of Eq. (2) as follows:

$$\widehat{r}_{h\ell}(n_1,n_2) = \frac{1}{N_1N_2}\sum_{k_1=-M_1}^{M_1}\sum_{k_2=-M_2}^{M_2}\widehat{R}_{h\ell}(k_1,k_2)W_{N_1}^{-k_1n_1}W_{N_2}^{-k_2n_2} \quad (3)$$

$\widehat{r}_{h\ell}(n_1,n_2)$ ranges in value from 0 to 1 and is a measure of the similarity of two images. The POC function itself is used to evaluate the similarity between two events, but a method to evaluate the degree of similarity among AE events is needed. The method proposed here uses peak values of the POC function for an AE cluster analysis.

To group AE events, a matrix consisting of the peak values of the POC function calculated for all combinations of two waveforms is defined. For a total of Q waveforms, the matrix is defined as follows:

$$\mathbf{X} = [R_{h\ell}] \quad (4)$$

$$R_{h\ell} = Max[\widehat{r}_{h\ell}(n_1,n_2)] \quad (h,\ell = 1,\ldots,Q) \quad (5)$$

The rows of $\mathbf{X}$, that is, $R_{h1}, R_{h2},\ldots,R_{hl}$, correspond to observation vectors, which are the peak values of the POC function calculated between the h-th and l-th AE events. A distance measure is needed for the cluster analysis to sort the observations into subsets. Here, the city-block distance is used as the distance measure; thus the distance between the s-th and t-th row vectors is given by

$$d_{st} = \sum_{i=1}^{L}|R_{si} - R_{ti}| \quad (6)$$

A rule is also needed to determine the distance between clusters after several AE events have been linked [10]. In this paper, Ward's method, which maximizes at each step the ratio between the variances within clusters and the variances between clusters [7,8,11], is introduced for this purpose. Thus, this POC and cluster analysis method not only identifies groupings of similar AE events but also clarifies the linkages among AE events, and the analysis results are presented as a hierarchical tree, on which each cluster is a distinct branch.

3. Application to actual AE events and discussion

POC of time-varying spectral representations (TVSPs) of AE data makes it possible to evaluate in the time–frequency domain the similarity of waveforms for which both the frequency content and signal amplitude change with time. I used the TVSP of an AE signal to represent a waveform image [12] corresponding to the $f_h(n_1,n_2)$ term in Eq. (1). Because the TVSP resolves the AE into frequency components that change with time, TVSPs can express the characteristics of an AE wave as the convolution of the source function and the transfer function of the wave propagation path.

In this paper, the POC function is calculated by using TVSPs of AE events for all possible combinations of two events. Because the POC function evaluates the similarity between two images and is calculated using the TVSPs of the waveforms, the evaluation takes account of the similarity of frequency content, frequency distribution, and wave attenuation with time, even though the cross-correlation and coherence functions cannot be used to evaluate changes in waveform characteristics, such as decreasing amplitude, with time. The cross-correlation and coherence functions are calculated using time-series data for a part of each wave form, and the similarity of the waveform parts are evaluated. The result is sensitive to the time-window length and the part used for the calculation because AE signals are usually unsteady [5]. Fig. 1 shows the waveforms of two local earthquakes, which occurred west of Sendai, Japan, at a depth of about 12 km. The TVSPs were calculated using the fast Fourier transform algorithm, and the time window for the calculation was moved along the time axis. The POC function comparing the two events is shown in Fig. 2, and the 2D cross-correlation of their time-varying spectra is shown in Fig. 3. 1D and 2D cross-correlation functions are often used to evaluate the similarity of time-series data and two-dimensional images, respectively. The peak of the POC function (Fig. 2) is sharper and narrower than that of the cross-correlation function (Fig. 3), making the former easier to use to judge the similarity of two waveforms [13]. In this case, the peak value of the POC function is 0.7 and its half-width in the frequency (n_1) axis direction is 0.5 discrete data point, respectively (Fig. 2).

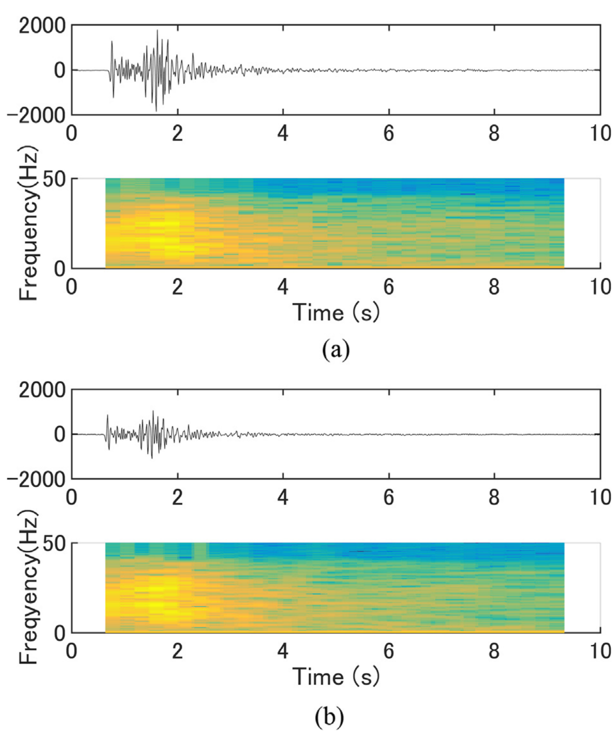

Fig. 1. Waveforms of two local earthquakes that occurred west of Sendai, Japan, at a depth of about 12 km and their time-varying spectra.