Automatic microseismic event detection and location with a RMS velocity and surface data

Xiong Zhang[1], Wei Zhang[2], Jie Zhang[1], [1]University of Science and Technology of China, [2]Southern University of Science and Technology*

Summary

The signal-to-noise ratio of microseismic data is generally low for surface monitoring due to the near-surface attenuation, relatively long propagation path, source radiation pattern, and small magnitude of the events. In addition, the uncertainty of the velocity model for the microseismic applications may be large because of limited information from sources such as perforation shots. To solve the above problems, we develop a time domain approach for event detection and location, in which we first scan a RMS velocity using the perforation shot event, which may not be clearly seen in the seismic data, and then detect and locate the microseismic events simultaneously by stacking data using the RMS velocity. Similar to the velocity analysis in the seismic reflection data processing, we stack the waveform data of the perforation shot along the hyperbolic curve and pick the maximum stacking energy to obtain the RMS velocity. We can then derive the average velocity using the known depth of the perforation shot. The subsequent microseismic events are then detected and located with the similar stacking procedure using the RMS velocity and average velocity. Synthetic examples show that the stacking image with the RMS velocity can help recover the true source locations reasonably well, and the horizontal location parameters are constrained better than the depth parameter. We apply the method to real data, and the results suggest that the approach can effectively detect events with low signal-to-noise ratio in an automatic fashion.

Introduction

Passive microseismic monitoring has been widely utilized in many fields, such as mining, geothermal, and gas/oil industries (Pearson, 1981; Mendecki, 1993). For example, microseismic activities offer valuable information for mapping fractures in shale gas development. The surface monitoring is an effective approach to determine the horizontal event locations, because a large areal spread of receivers on the surface can be deployed in comparison with downhole monitoring (Duncan and Eisner, 2010).

However, the signals recorded on the surface may be too weak because of the small magnitude of the microseismic events and the strong attenuation in shallow weathering layers of sedimentary basins (Eisner et al., 2010). The SNR of the P/S wave arrivals may be low and the P/S arrivals cannot be detected at individual receiver on the surface. The location techniques for surface monitoring usually involve stacking or time-reverse modelling (McMechan, 1982; Kao and Shan, 2004; Gajewski et al., 2007); thus, the traveltime picking for the low SNR waveforms can be avoided. The waveform data recorded on the surface is back propagated to the origin of the source using the time-reverse modelling methods (McMechan, 1982; Gajewski and Tessmer, 2005; Artman et al., 2010). For the stacking methods, the traveltime table for the potential location grids is calculated in advance, and the energy at each location node is evaluated by stacking the waveforms along the traveltime curve of all the receivers (Kao and Shan, 2004; Liao et al., 2012; Grigoli et al., 2013; Anikiev et al., 2014). The grid with the maximum stacking energy is then automatically assigned to be the likely event location. Gajewski et al. (2007) develop a migration-type approach with the back-projection of the recorded seismic waveforms. Gharti et al. (2010) propose to project seismic waveforms into the ray coordinate system, compute their envelopes, and stack along the moveout of P- and S-wave arrival times. Haldorsen et al. (2013) utilize a semblance-weighted deconvolution in the migration-based method. Zhang and Zhang (2013) apply the crosscorrelation imaging condition on the semblance-weighted stack to extract the coherence of the P and S waves in the array data.

In addition to the location method, the velocity model for location plays an important role to determine the accurate locations of the microseismic events (Usher et al., 2013). The traditional stacking methods may require a well-resolved velocity model, which may be calibrated with perforation shots (Warpinski et al., 2003). Generally, we can assume that the velocity is 1D and can initially be derived from the well logs but the velocities should be calibrated with the perforation shots (Warpinski, 2003; Bardainne and Gaucher, 2010). With the arrival times of the perforation shot, a grid search method can be utilized to find the velocity values in each layer through fitting the arrival times (Oye and Roth, 2003). However, the velocity model may be poorly constrained because of the limited available sources (e.g. perforation shots) for the surface monitoring. The corresponding waveform data of the perforation shots may contain plenty of noises for the surface monitoring, which may result in the difficulties of P/S wave arrival picking or the relative arrival time calculation by cross correlation. In this study, we attempt to derive an effective RMS velocity by stacking the perforation shot data and simultaneously detect and locate the microseismic event. NMO correction and velocity analysis are successfully applied in the seismic reflection data processing based on the horizontal layered model assumption (Sheriff and Geldart, 1995; Yilmaz, 1990). We attempt to apply a single RMS velocity instead of the 1D layered velocity model for automatically detecting and locating events by borrowing the similar concept from seismic data processing.

Method

We utilize the known locations of the perforation shots and the corresponding waveforms with strong noises to obtain the RMS velocity instead of the layered velocities; then the subsequent events are stacked with the RMS velocity to obtain the event locations during hydraulic fracturing. The origin time of the source is unknown for the microseismic data. We derive the relationship between the origin time and the average velocity of the layered model; therefore we scan the average velocity instead of the origin time when solving for the RMS velocity.

RMS velocity stacking with known location

We assume that the waveform of the perforation shot is contaminated with strong noises, and the shot location is known to us. The relationship between the location, the RMS velocity, and the average velocity is as following:

$$\left(t_p - T_0\right)^2 = \frac{x^2}{V_{rms}^2} + (t_0 - T_0)^2, \tag{1}$$

$$t_0 - T_0 = \frac{h}{V_a}, \tag{2}$$

where t_p is the arrival time of the P wave at each receiver; x is the horizontal distance between the shot and receiver; t_0 is the arrival time of the P wave when $x = 0$; T_0 is the origin time of the source; h is the depth of the source; V_{rms} and V_a are the RMS and average velocities respectively. Equation 1 is associated with the Dix's formula; however, the source is not on the surface in our application. The arrival time represents the direct wave rather than the reflection. The origin time T_0 is generally unknown for the recorded waveform data, and we can calculate the traveltime, $t_0 - T_0$, from the source to the receiver at zero offset using the average velocity and source depth. Therefore, we can obtain the following equation after eliminating the original time in the equations 1&2:

$$t_p = \sqrt{\frac{x^2}{V_{rms}^2} + \frac{h^2}{V_a^2}} + t_0 - \frac{h}{V_a}, \tag{3}$$

For the RMS velocity stacking with a known location, equation 3 depicts the relationship between the arrival time at each receiver and the velocity parameters. Each vector of the parameters (t_0, V_a, V_{rms}) determines a traveltime curve which consists of the arrival times at all the receivers. We can stack the waveforms in a time window along the traveltime curve using the semblance (Neidell and Taner, 1971; Kiselevitch et al., 1991):

$$f(t_0, V_a, V_{rms}) = \frac{\left[\sum_i^{nr} u_i\left(t_p^i(t_0, V_a, V_{rms})\right)\right]^2}{nr\sum_i^{nr}\left[u_i\left(t_p^i(t_0, V_a, V_{rms})\right)\right]^2}, \tag{4}$$

where nr is the number of receivers; u_i and t_p^i are the waveform data and arrival time at the i^{th} receiver. We stack the waveforms along the arrival time curve determined by the given parameters(t_0, V_a, V_{rms}); then the energy of the stacked waveform $f(t_0, V_a, V_{rms})$ can be calculated. The maximum value of the energy of the stacked waveform $f(t_0, V_a, V_{rms})$ is associated with the possible best RMS and average velocities. The best RMS and average velocities can be utilized in the subsequent event location process.

Location with the RMS velocity

The RMS and average velocities are obtained from the data of noisy perforation shot. The event locations during hydraulic fracturing can be determined through the same stacking concept utilizing the obtained RMS and average velocities. The solutions which we attempt to search for include the event location parameters $\left(s_x, s_y, h\right)$. The horizontal distance x between the event and the receiver can be determined using the following equation in the layered medium:

$$x^2 = (s_x - r_x)^2 + \left(s_y - r_y\right)^2, \tag{5}$$

where the r_x and r_y are the receiver location coordinates; s_x and s_y are source coordinates in horizontal direction. For the given parameters$\left(t_0, s_x, s_y, h\right)$, the arrival time curve which consists of all the arrival times at the receivers is determined by the equation 3&5. We can stack the waveforms along the arrival time curve to obtain the energy value which is a function of the source location:

$$f\left(t_0, s_x, s_y, h\right) = \frac{\left[\sum_i^{nr} u_i\left(t_p^i\left(t_0, s_x, s_y, h\right)\right)\right]^2}{nr\sum_i^{nr}\left[u_i\left(t_p^i\left(t_0, s_x, s_y, h\right)\right)\right]^2}, \tag{6}$$

In our application, the event detection and location processes can be performed simultaneously. The equation 6 depicts a 4-D image function, and we scan the waveforms from the beginning to the end to detect the events with large stacking energy. To evaluate the location result reliably, we construct a possibility density function from the stacking image function (equation 6) in the same way as the traditional analysis method (Tarantola, 2005; Anikiev et al., 2014). Both the average and uncertainty of the event locations can be estimated by the possibility density function.

Synthetic examples

We test the methodology with synthetic examples as shown in Figure 1. The layered velocity model is commonly assumed in the microseismic data processing. However, the velocity in the near surface may be complex and deviated from the layered media assumption. To simulate the effects of the near surface, we assume that there are five anomalies below the receiver arrays, and there are 70 receivers with an interval of 50 m deployed along the cross line as in Figure 1. The 18 events utilized to generate the waveform data are assumed in a rectangular box (Figure 1). There are 9 events located from 950.0 m to 1050.0 m in x direction, from 950.0 m to 1050.0 m in y direction, and 1500.0 m in depth. The horizontal locations of the other 9 events are the same, but the depth is 1400.0 m. We utilize the event located at (1000.0, 1000.0, 1500.0) m to solve for the RMS velocity (Figure 2). The input waveform data is contaminated with 35% Gaussian noise, thus, it is difficult to pick the direct P waves manually as shown in Figure 2b. However, the arrival time curve produced by the point with maximum stacking energy can well fit the waveform data (Figure 2). In the real application, we can also manually pick the point with large stacking energy to obtain the RMS velocity.

The microseismic events can be located with a RMS velocity obtained from the stacking results. We assume the 18 events in Figure 1 are recorded continuously. Figure 3a & 3b show the synthetic waveforms recorded continuously for the first 9 events, and the input waveforms are contaminated with 35% Gaussian noises. For each time parameter t_0, we can scan each possible locations on the spatial grid to obtain the cell with maximum stacking energy; and Figure 3c shows the energy trace for each t_0 and the corresponding location parameters with maximum energy. The locations in the time window with low stacking energy seam to be distributed randomly because there is no event. We pick the points at the peak of the stacking energy trace to obtain the event locations (Figure 3c). We can also calculate the average value of the location parameters according to the possibility density function created from the stacking energy after picking the time t_0 (Figure 4). Figure 4 shows that the horizontal location parameters of the 18 events are well recovered in comparison with the true solutions. The average horizontal location errors between the calculated locations and the true locations are within 30.0 m; however, the depth error is much larger than the horizontal location error. The location uncertainties are also estimated for the 18 events (Figure 4). The average location uncertainty in horizontal directions of the 18 events is about 95 m, and the average location uncertainty in depth is about 132 m.

Field data examples

We utilize the real waveform data to test the methodology. The stage of the hydraulic fracturing is located at about 4100.0 m in depth and horizontally in the middle of the cross-lines of the receiver arrays. The perforation shots are recorded by 531 receivers in total, and the lengths of the two survey lines are about 5000.0 m and 6000.0 m respectively. We utilize the perforation event located at (-110.94, -141.33, 4087.8) to scan the RMS velocity through the stacking method as shown in Figure 5. The waveform data from 0.0 s to 1.0 s is scanned with an interval of 2.0 ms; and the velocity range is set from 800.0 m/s to 10000.0 m/s with a scan interval of 100.0 m/s. Figure 5b shows that the velocity is approximately in the range of 2000.0 m/s to 6000.0 m/s in which the stacking energy is much larger than the other areas. The RMS velocity at the point with maximum energy is 3400 m/s, and the corresponding average velocity is 1900 m/s. The synthetic arrival time curve of the best solution can well match the waveform phases although it is difficult to pick the arrival time of the phases manually.

We locate an event using the RMS velocity obtained in Figure 5b. The microseismic events by the hydraulic fracturing are recorded by 1788 receivers in total. We utilize the RMS velocity inverted from the perforation shot recorded by part of the 1788 receivers to locate the event because of the 1D layered velocity assumption. The search range of the location is from -800 m to 800m in x and y direction; in addition, the location intervals in both directions are 20 m. We scan the origin time in the application, and the depth is converting from the zero-offset traveltime. We obtain the corresponding spatial distribution of the stacking energy as shown in Figure 5d. The stacking image shows that the resolution of the horizontal location parameters is much higher than depth.

Conclusions

We develop new event detection and location, and velocity scanning and stacking methods based on the RMS velocity assumption. We first utilize the perforation shot with known location to perform the stacking algorithm, and the RMS and average velocities can be obtained. The subsequent microseismic events can be located by scanning the waveform data with the RMS and average velocities. The event detection and location can be performed simultaneously without preserving the traveltime table and performing the ray tracing. The traveltime curve can be calculated with the simple analytical solutions during the stacking process.

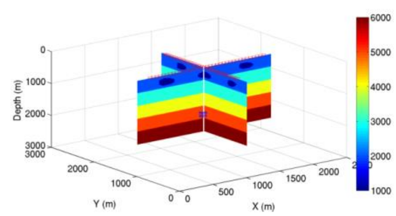

Figure 1: The velocity and geometry. The red triangles on the surface are the receivers and the blue stars denote the 18 events. There are five low velocity anomalies under the receiver arrays.

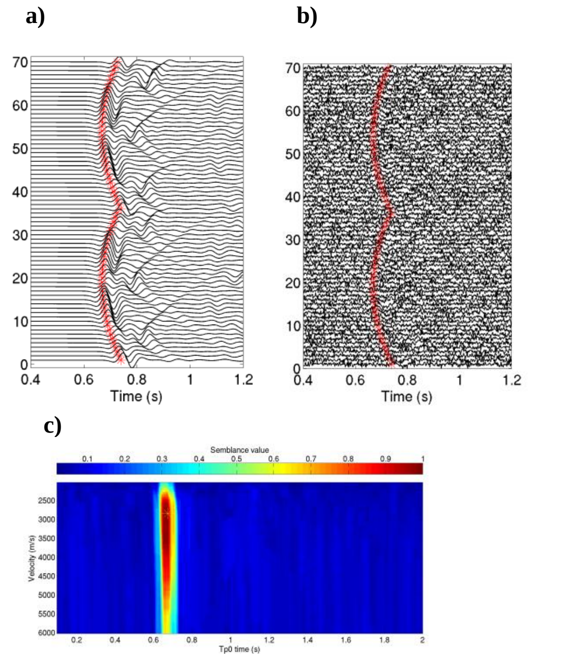

Figure 2: The result of the RMS velocity scan. (a) The synthetic waveform generated with the event location (1000.0, 1000.0, 1500.0) m. (b) The synthetic waveform contaminated with 35% Gaussian noises. (c) The stacking image for the RMS velocity. The RMS velocity at the picked yellow star is 2850 m/s, and the corresponding average velocity is 2350 m/s. The corresponding arrival time curve (red dots) is shown in the synthetic waveform figures.

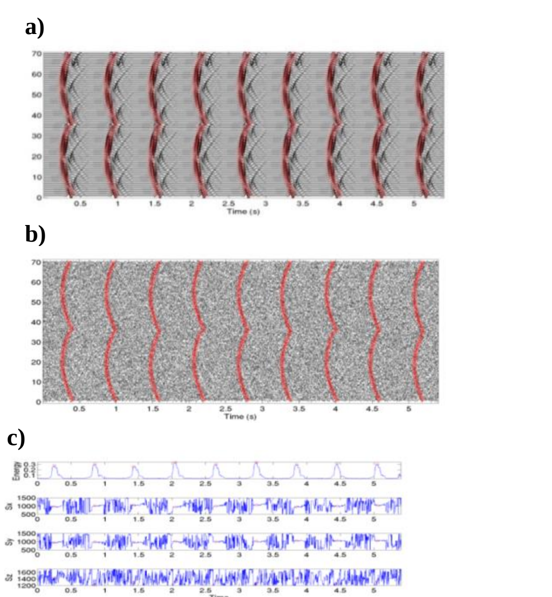

Figure 3: The event location result with the RMS velocity obtained in Figure 2. (a) The input waveforms without noise; (b) the input waveforms contaminated with 35% noise; the red curve represents the traveltimes calculated with the location results; (c) the stacked energy trace and best locations for the corresponding time sample.

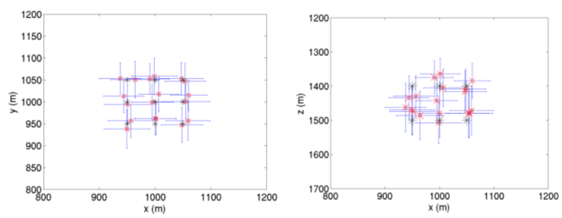

Figure 4: The true (black) and calculated (red) locations. The points with large stacking energy are picked as the events.

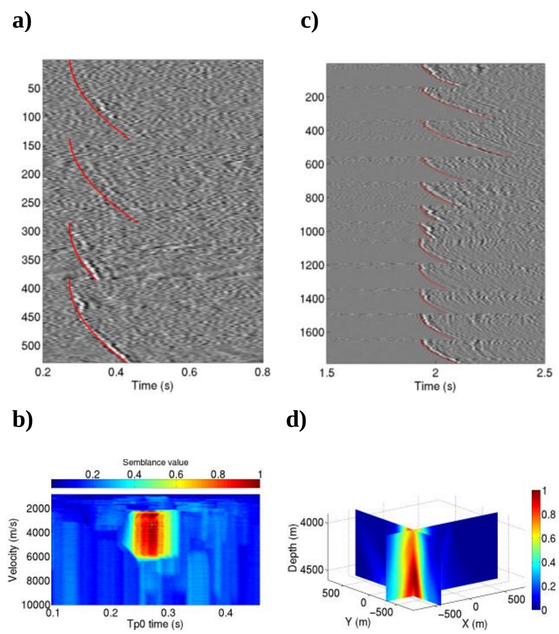

Figure 5: (a) The original waveform of the perforation shot utilized to calculate the RMS velocity. The red line denotes the traveltime curve of the best solution. (b) The stacking image for the RMS velocity. The yellow star represents the picked RMS velocity 3400 m/s, and the corresponding average velocity is 1900 m/s. (c) The original waveform of a located event; the traveltime curve (red) is calculated with the location result (-421.8, -287.1, 4279.9) m. (d) The spatial distribution of the stacking energy for locating the event.

Acknowledgements

We appreciate GeoTomo Hefei for the support of this research, and for allowing us to use the MiVu^{TM} software package to perform this study.