Comparison of stacking methods with a depth model or with a RMS velocity for automated microseismic event location from surface monitoring

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Summary

An accurate velocity model is essential for microseismic event location, especially for low signal-to-noise ratio data from surface monitoring. Both a 1D layered velocity model and a RMS velocity may be used in the automated stacking method. We compare the stacking methods with a 1D layered velocity model or with a single RMS velocity respectively. The synthetic examples show that the horizontal coordinates of the event locations can be constrained well with both methods, and the resolutions are nearly identical, but the depth resolution is poor with both methods. However, estimating an overall RMS velocity is much easier than establishing an accurate 1D layered model. Therefore, the automated stacking method using a RMS velocity is more practical when dealing with real data. We demonstrate with real data that the RMS velocity stacking method produces reliable results.

Introduction

The surface monitoring data usually show a low signal-to-noise ratio (SNR) because of small magnitude of the events and strong attenuation along propagation path (Eisner et al., 2010). The Source-Scanning Algorithm (SSA) is developed for imaging the distribution of seismic sources in both time and space which is based on a 1D layered velocity model (Kao and Shan 2004). An improved SSA (ISSA) is developed to delineate the complex distribution of aftershocks without time-consuming and labor-intensive phase-picking procedures (Liao et al., 2012). In the stacking method, the point with the maximum energy is the most likely event location. A 1D velocity model from roughly event depth up to surface is usually utilized, and it can be obtained from well logs and/or perforation data processing, but the model accuracy is often limited because of long depth range, and the near surface complexity. The velocity model is an essential factor for locating microseismic events. The scanning stacking method utilizing a single RMS velocity instead of a layered depth velocity model seems more practical (Zhang et al., 2017). This method is easy to apply, and it can achieve similar location results in comparison with the stacking method utilizing a 1D layered velocity model.

In this study, we compare the two scanning stacking methods utilizing a 1D layered velocity model or a RMS velocity with synthetic and the field data examples. In addition, we analyze the event location error and uncertainty in horizontal and depth dimensions.

Methods

The stacking method with a 1D layered velocity model

The SSA was originally designed to locate seismic events (Kao & Shan 2004). It is a systematic grid-search method that locates the sources in temporal and spatial distribution based on the maximum brightness. We calculate a traveltime table in advance for the entire model grids. For each location node, a brightness value is calculated by stacking the waveform data along the traveltime curve consisting of the arrival time at each receiver. In our application, we utilize the following equation to evaluate the stacking energy at each location:

$$F(\tau, s_x, s_y, h) = \left| \sum_{i}^{nr} u_i(t_p^i(\tau, s_x, s_y, h)) \right| \quad , \tag{1}$$

where τ is the origin time of the source; $t^i_p(\tau, S_x, S_y, h)$ is the arrival time at the i^{th} receiver; S_x, S_y, and h are the horizontal and depth coordinates, u_i is the waveform data at the i^{th} receiver. We calculate the traveltime from the event location to the points at the interface of the layer, and the raypath with minimum traveltime is selected as the solution associated with t^i_p. To accelerate the speed of the stacking algorithm, the traveltime table is loaded into the computer memory during the stacking process.

The stacking method with a RMS velocity

The stacking method with a RMS velocity for microseismic event location is developed by Zhang et al. (2017). This method requires an event with known location to obtain the RMS velocity and the average velocity for the entire model. Therefore, it is very easy to estimate the velocity values.

The relationship between location, the RMS velocity, and a mean velocity is as following:

$$t_p = \sqrt{\frac{x^2}{v_{rms}^2} + \frac{h^2}{v_a^2}} + t_0 - \frac{h}{v_a} \quad , \tag{2}$$

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 $x=0$; h is the depth of the source; v_{rms} and v_a are the RMS velocity and mean velocity, respectively.

We can stack the energy in a time window along the traveltime curve using the following equation:

$$f(t_0, v_a, v_{rms}) = \left| \sum_{i}^{nr} u_i(t_p^i(t_0, v_a, v_{rms})) \right| , \tag{3}$$

where *nr* is the number of receivers; u_i and t^i_p are the waveform data and arrival time at the i^{th} receiver. Then the maximum energy is related to the best RMS and average velocities.

We assume the source location is (S_x, S_y, h) then the horizontal distance x between the source and receiver is set as:

$$x^2 = (s_x - r_x)^2 + (s_y - r_y)^2, \qquad (4)$$

Where r_x and r_y are the receiver location in horizontal direction. The energy obtained by stacking the waveforms along the arrival time curve is given as following:

$$F(t_0, s_x, s_y, h) = \left| \sum_{i}^{nr} u_i(t_p^i(t_0, s_x, s_y, h)) \right|, \qquad (5)$$

Synthetic test

We first apply these two methods to synthetic examples as shown in Figure 1. We design a layered depth model in processing. The acquisition geometry of the test includes 50 receivers with an interval 50 m deployed along the cross line, and 12 events are represented by blue stars in Figure 1. There are 3 events located from 950.0 m to 1050.0 m in x direction, 1000.0 m in y direction, and 900.0 m in depth. The horizontal locations are the same but the depth of second 3 events is 950 m, the depth of third 3 events is 1000 m, and the depth of last 3 events is 1100 m.

We present a synthetic waveform generated for the event location (1050.0, 1000.0, 1100.0) m and data is contaminated with Gaussian noises as shown in Figure 2 and the RMS ratio between noise and waveform is 40%. Figure 2b shows that the arrival time curve produced by the point with maximum stacking energy can well fit the waveform data.

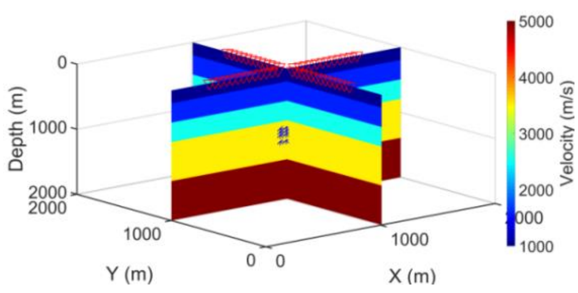
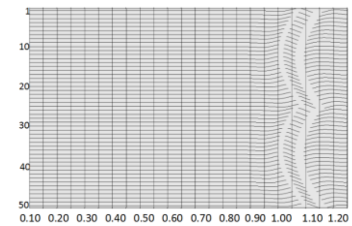


Figure 1: The velocity model and geometry of the test includes 50 receivers (red triangle) with an interval 50 m deployed along the cross line, and 12 events are represented by blue stars.

(a)



(b)

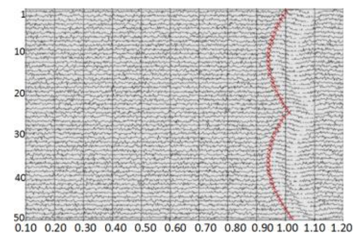
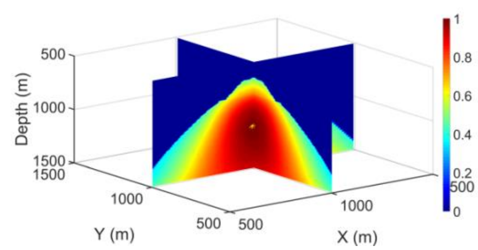


Figure 2: (a) A synthetic waveform generated for the event location (1050.0, 1000.0, 1100.0) m. (b) Above synthetics contaminated with Gaussian noises (SNR: 40%).

The most likely location is associated with the maximum energy value. The energy distribution of one event is displayed in Figure 3. Figure 3a and 3b show the imaging of the stacking energy based on 1D layered velocity model and RMS velocity respectively. They show a small difference of uncertainty on depth, but the uncertainty on horizontal direction in Figure 3a is obviously larger than that in Figure 3b.

(a)



(b)

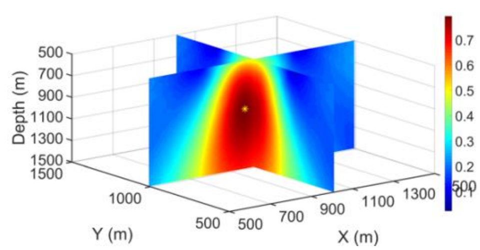
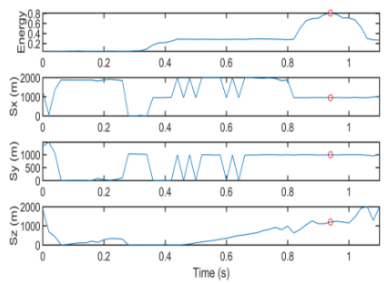


Figure 3: The stacking energy distribution of single event. (a) The result based on a 1D layered velocity model; (b) The result based on RMS velocity. The yellow star denotes the point with maximum stacking energy.

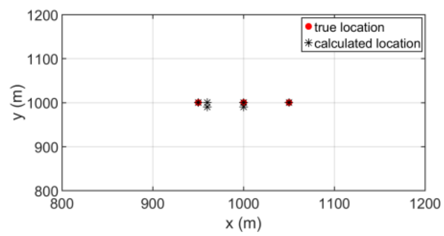
Comparison of two stacking methods for event location

We obtain the energy for each parameter t_0 and the corresponding location with maximum energy as shown in Figure 4a. Figure 4b, 4c, and 4d show the calculated locations of 12 events with a RMS velocity compared with the true locations in 2D planes. Figure 5a, 5b, and 5c show the calculated locations of 12 events with a 1D layered velocity model compared with the true locations in 2D planes. We find that the location error is smaller in horizontal direction than that in depth for both methods. Figure 6 shows that these two methods yield very similar results. The calculated error in x direction is approximately 20 m, 10 m in y direction, and 110 m in depth direction.

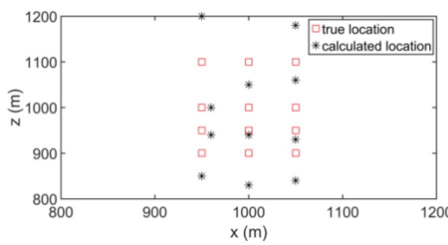
(a)



(b)



(c)



(d)

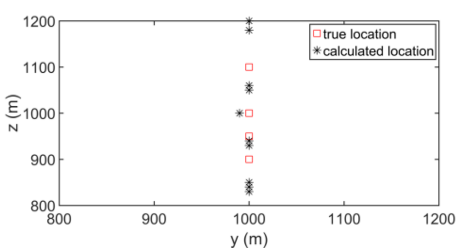
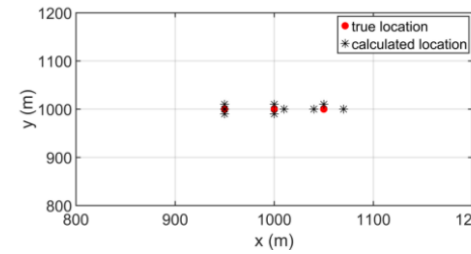
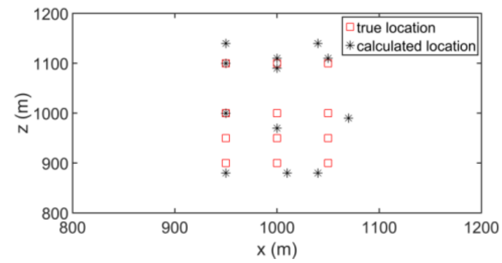


Figure 4: The RMS velocity results compared with the true location. (a) showing the energy for each parameter t_0 and the corresponding location with maximum energy (red circles). (b), (c), (d) showing the calculated locations of 12 events with RMS velocity compared with the true locations in x-y, x-z, and y-z plane respectively.

(a)



(b)



(c)

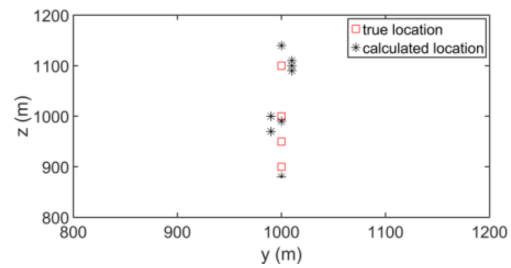


Figure 5: The calculated locations of 12 events with 1D layered velocity compared with the true locations in 2D planes. (a), (b), (c) showing the locations of 12 events in x-y, x-z, and y-z plane respectively.

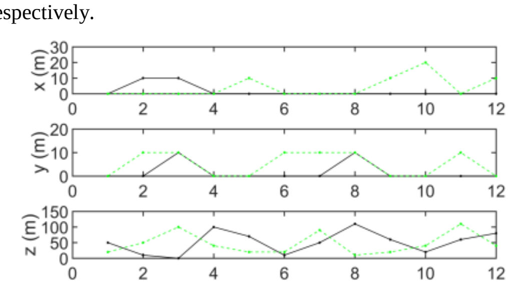


Figure 6: The calculated errors in x, y, and z direction. The black solid line represents the RMS velocity and the green dashed line represents the 1D layered velocity model.

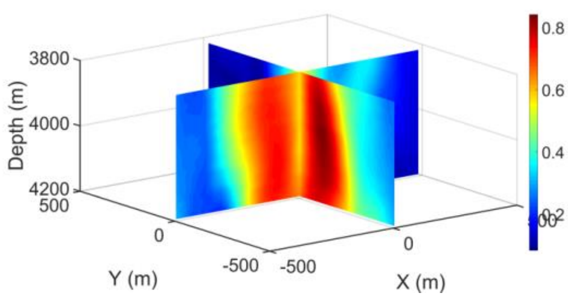
Comparison of two stacking methods for event location

Field data test

We utilize a real dataset to test the efficiency of the two methods. First, we utilize the perforation event located at (-110.94, -141.33, 4087.8) m to search an optimal RMS velocity through the scan stacking method. We obtain the RMS velocity with 3400 m/s and the corresponding average velocity is 1900 m/s. Secondly, the two stacking methods are applied to the location of microseismic events generated by hydraulic fracturing.

Figure 7 shows the stacking energy distribution of single event based on the 1D layered velocity model. The location deviation between the two methods is found as (0, 20, 110) m. We conclude that the resolutions of two methods are nearly identical and are much better in horizontal coordinates than that in depth. The location results of 3 real data events based on 1D layered velocity and RMS velocity in 2D planes are shown in Figure 8. The same number means the same single event is located by the two methods. The average location deviation between the two methods is found as (60, 47, 105) m. The comparisons of calculated locations by the two methods show similar results, and the resolution in horizontal direction is better than that in depth for both methods.

(a)



(b)

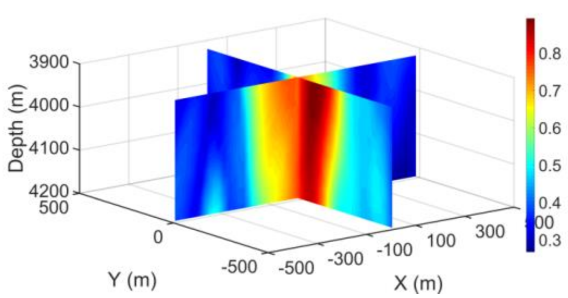
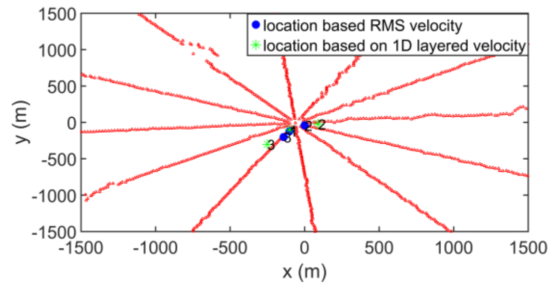


Figure 7: The stacking energy distribution of single event. (a) The result based on a 1D layered velocity model; (b) The result based on RMS velocity.

(a)



(b)

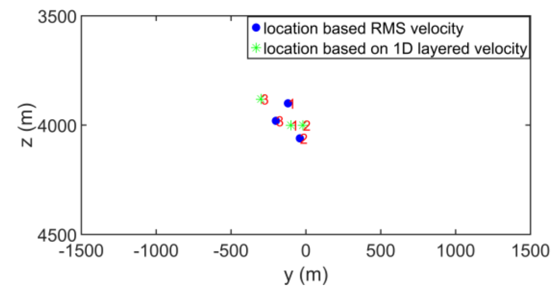


Figure 8: The location results of 3 events based on 1D layered velocity and RMS velocity in 2D planes. The same number means the same single event is located by two methods. (a) showing the locations in x-y plane with two methods. The red stars shows the receiver geometries for the microseismic events generated by hydraulic fracturing. (b) showing the locations in y-z plane with two methods.

Conclusions

We compare two scanning stacking methods: one using a 1D layered velocity model, and the other using a single RMS velocity. The synthetic and examples show that the event locations can be constrained well by both methods in the horizontal direction, and the resolutions are nearly identical. In addition, the uncertainty of the depth is larger than the horizontal coordinates for both methods. The real data test indicates that both methods yield the similar results. However, it is much easier to infer an accurate RMS velocity than a 1D layered velocity model. Therefore, the RMS velocity method is more practical.

Acknowledgments

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