Microseismic search engine

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Summary

Similar to a web search engine, we develop a microseismic search engine that can help to estimate event location, magnitude, and focal mechanism all together in less than a second. The method includes the calculation of all possible microseismic events over a 3D grid with a known velocity model. We then index and rank all of the seismic waveforms following the characteristics of phase and amplitude information and create a database by applying multiple randomized K-dimensional tree method. When a microseismic event occurs, approximate best matches to the entry waveform shall be found immediately by comparing the input data with the characteristic features in the database. The method does not just return one solution, but a series of solutions just like the web search engine. Thus, the solution space delineates the resolution and uncertainty of the results. Also similar to a web search engine, it does not require any input parameter or processing experience, thus the solutions are the same for any user. We demonstrate the method with both synthetic and real data. It shows a great potential for routinely monitoring microseismic events in real time during hydraulic fracturing operation.

Introduction

When a microseismic event takes place during hydraulic fracturing operation andis recorded by monitoring receivers in borehole or on the surface, we want to use the data to infer and report its location, magnitude, and source focal mechanism as fast as possible.If such information could be determined the instant it occurred, site engineers could assess the effectiveness of hydraulic fracturing operation immediately and minimize operation cost and resources.

Tremendous efforts in earthquake seismology have been made for estimating earthquake parameters fast for early warning purpose (Allen, 2011). Current state-of-the-art technology allows reporting earthquake location and magnitude within 5 seconds after the P-wave arrival with some success (Nakamura and Horiuchi, 2008), and new published methods allow inverting source focal mechanism in a few minutes (Guilhem and Dreger, 2011). In microseismic studies, a common fast approach for locating microseismic events is to use a grid search method (Warpinski, 2009). The method calculates traveltimes from each receiver to every grid point in the subsurface for both P- and S-waves, and all of these traveltimes are stored in memory. When actual time picks are determined, the picked times can be compared with the calculated values throughout the entire grid, and the point with the closet match is the best-fit source of the microseism. Because the method involves traveltime picks, and a hydraulic fracturing project may trigger a few hundreds or thousands of microseismic events interfered with significant noise, applying automatic picking may be difficult. There are also many other event location strategies, which fit essentially into the loose category of migration and require substantialprocessing time (Rentsch et al., 2010; Haldorsen et al., 2012). Note all of these methods determine event locations only, additional efforts need to be made if the information of magnitude and focal mechanism of the microseismic events are needed.

By applying Internet search technology, we attempt to estimatemicroseismic event location, magnitude, and focal mechanism all together automatically within a second for each event.Similar to a web search engine for document or image retrieval, we developedamicroseismic search engine to estimate complete source parameters by searching similar microseismic waveforms from a large database. The database could include millions of theoretically calculated seismograms with known source information over a 3D grid. Our objective is to find the best matches to any new microseismic full waveform from the database. It may require several hours to find the best matches from such a large dataset by brute force. However, with the computer search technology and new ideas for indexing a seismogram dataset, the best matches can be found in a second. The key is to find the approximate nearest neighbors to an entry instead of performing an exact search.

Fast image search technology

Fast search technology in computer science has been well developed (Henzinger, 2007). Many methods in this category have been successfully applied to retrieve words, images, and videos from the Internet-sized datasets (Muja and Lowe, 2009). Following example shows that searching similar pictures to an entry among 10 millions of images could take as little as 0.1 second by applying a fast search algorithm (Zhou et al., 2011).

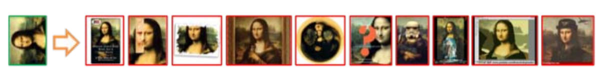

Figure 1: search similar pictures among 10 millions of images in a database and the search results (Courtesy of Zhou et al., 2011).

If we take seismogram as an image, finding best matches to an entry among a large database is then becoming an image search problem. This database represents full waveforms of all of the possible microseismic events associated with a specific velocity model and monitoring geometry. Ourapproachspecifically applies the Multiple Randomized K-Dimensional (MRKD) tree method (Silpa-Anan and Hartley, 2008). It involves creating multiple tree structures from datasets by splitting the data in half at each level of the tree for a time sample for which the data exhibits the greatest variance in amplitude. The database captures the most prominent characteristics in the microseismic data with limited samples. We then search the best matches following the tree structure when an entry comes in.

Synthetic example

The method of microseismic search engine can be applied to any monitoring geometry. The following (Figure 2) shows a synthetic example with 3-C receivers placed on the surface. With a 1-D velocity model, we calculate the full elastic waveforms of potential microseismic events over a grid of spatial position in the subsurface, magnitude, and focal mechanism. As a result, 170,250 microseismic waveforms are generated and included in the database.

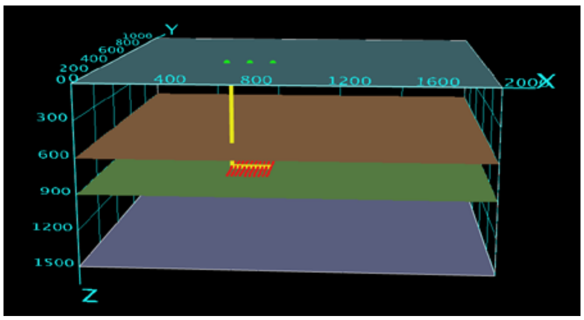

Figure 2: a synthetic velocity model, three receivers, and schematic display of all potential microseismic events in the shale layer.

After we create the database, we select an arbitrary event to be an input for testing the search engine. For multiple receivers, we actually merge all of the data traces into a super trace, and use the super trace as an entry. Figure 3 shows the search results and display merged vertical component of the three surface receivers. The super trace for search actually includes vertical components and also two horizontal components. Just like a web search engine, the return of a search includes a list of results. In Figure 3, every 100th search results are displayed. On the right hand side, it displays cross-correlation coefficients.

Further numerical experiments reveal a few important features of the microseismic search engine. The search method looks for approximate solutions to the entry rather than an exact solution, thus, this fits in seismic problems well. The search results are all relative to one another within the database. Therefore, the database does not have to be perfect in terms of simulating the data, as long as the search can rank the solutions correctly. This is different from full waveform inversion, where it requires that the forward modeling must simulate the data accurately. Further, the search results include a solution space, which can help us to understand the nonuniqueness of the picked solution.

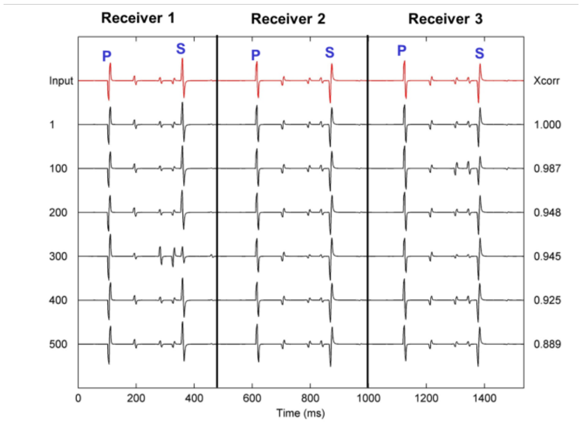

Figure 3: a super trace of the entry event (in Red), and every 100th search results displayed by similarity to the entry event.

Real data example

We shall demonstrate examples with real data acquired from a hydraulic fracturing operation for shale gas production. In this case, we use a downhole receiver array to monitor microseismic events. Prior to the operation, we build a velocity model from well log and take about an hour to calculate synthetic database that includes all potential microseismic events in the shale layer.

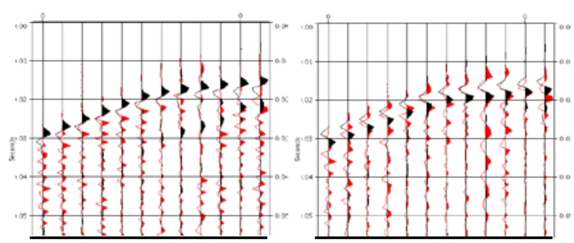

Figure 4: real microseismic event 1 (Red) and the best match (Black) found from search engine. The left plot shows vertical component, and the right plot shows X component.

The entry event shown in red in Figure 4 is a very small one, with moment magnitude about -2.5. From downhole receivers about 400m away, it records S waves only and P waves are completely missing. The issue of low signal-to-noise ratio in microseismic studies is a common problem. It could be even more difficult to record quality data from surface due to near-surface attenuation and longer propagating distance. Figure 4 shows that the microseismic search engine finds the best synthetic match from database and it fits S-wave data well. Since synthetic data in the database includes information of location, magnitude, and focal mechanism, these parameters of the actual real event are then obtained (Figure 5).

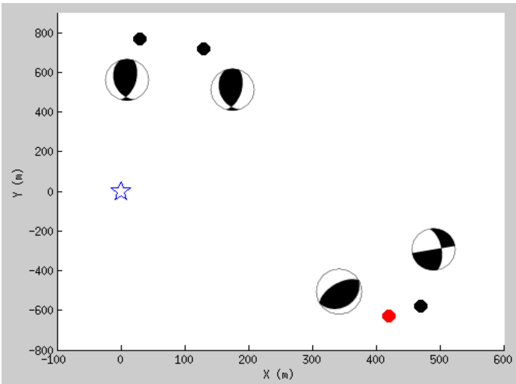

Figure 5: Plan view of event location for matching event 1. Top 4 solutions returned from the search engine including their focal mechanism. The one in red is the best solution. Star marks the location of the monitoring well.

Figure 5 indicates that full waveform information is strongly coupled with source focal mechanism. The first 4 best solutions are not necessary at close locations.

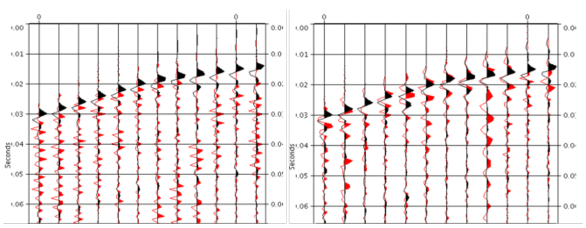

Figure 6: real microseismic event 2 (Red) and the best match (Black) found from search engine. The left plot shows vertical component, and the right plot shows X component.

Figure 6 shows the best match returned from the search engine for another small magnitude event, which also misses P waves completely. Figure 7 shows the top 4 solutions. The search engine finds the best S-wave match in this case. Figure 4 and 6 show that the best matches fit the large amplitude S waves, but not the reverberation and noise after that.

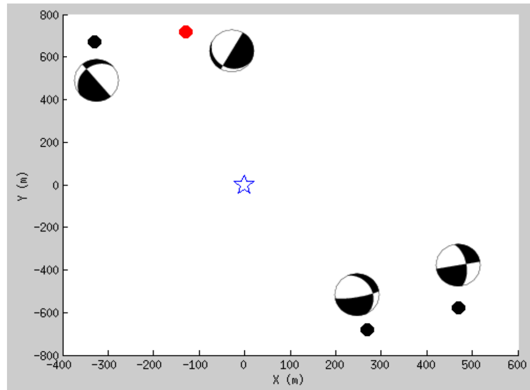

Figure 7: Plan view of event location for matching event 2. Top 4 solutions returned from the search engine including their focal mechanism. The one in red is the best solution. Star marks the location of the monitoring well.

a) Event 1 b) Event 2

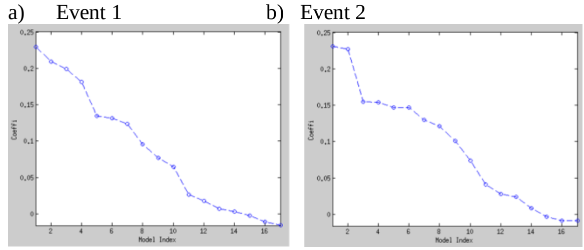

Figure 8: Correlation between the entry data and the top 17 best matches from the search engine: a) search event 1; b) search event 2.

Unlike synthetic data search that the best match returns cross-correlation coefficient 1.0, the value is much smaller for searching real data, slightly larger than 0.1 in both cases (Figure 8). Figure 8 also shows that the best match is well constrained because the value of other nearest neighbors decreases quickly.

These examples demonstrate that microseismic search engine can handle the data with low signal-to-noise ratio fairly well. In the absence of P waves, it can still find the best matches to S waves and utilize the full data content to determine event information.

Conclusions

We introduce a microseismic search engine method to process data in real time. This method involves preparing a database prior to the field operation, and estimating location, magnitude, and focal mechanism of each event in less than a second. This method does not require any input parameter, thus, the results are independent on user's experience. Finding best matches from a database is different from full waveform inversion, which requires that the forward modeling must be able to simulate microseismic wavefield accurately. In really, that is very difficult considering complex media effects including 3D structure, attenuation, anisotropy and others. Finding best matches, on the other hand, returns a relative estimate and ranking within a database.

Acknowledgements

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