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Surface passive seismic monitoring by the local use of semblance

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SUMMARY

Monitoring of passive seismic sources generated by mining activities and hydraulic fracturing has an important role in hazard analysis and in development of unconventional reservoirs. Surface arrays are vastly used in such monitoring scenarios with the advantage of wider spatial monitoring aperture, thus monitoring larger volumes over downhole arrays. However, signal-to-noise ratio of surface array records is naturally low. That makes application of coherency-based techniques an appropriate option for surface monitoring.

Polarity variations corresponding to the source mechanism across the moveout curves/surfaces is a complicating task in the use of coherency-based monitoring methods to locate passive seismic events. To overcome this issue, we suggest a straight-forward approach that applies semblance, as a coherency analysis tool, on separate clusters of stations followed by averaging the results from all the clusters. To evaluate the performance of the suggested approach, we applied it on a semi-synthetic passive seismic data example generated from a reverse-oblique source and compared the result with the outcome from application of the classic coherency-based technique. It shows the ability of the suggested method to overcome polarity variations task, without conducting any polarity correction step.

Key words: passive seismic, source mechanism, semblance, clustering

INTRODUCTION

The study of the distribution of passive seismic sources is a useful tool in mining industry and unconventional reservoir development in the oil-and-gas industry (Chambers et al., 2014; Khoshnavaz et al., 2016). Passive seismic monitoring has been used in the mining industry over the past century with the main application of hazard management in deep hard rock mines by monitoring of mining-induced seismicity (Mikula et al., 2008). Employment of passive seismic monitoring in the oil-and-gas industry is comparatively new and includes the monitoring of passive seismic events induced by hydraulic fracturing. Monitoring of the distribution of microseimic events induced by hydraulic fracturing provides important information about fracturing process, allowing optimization of reservoir drainage and well design (Maxwell, 2014).

Surface passive seismic surveys are commonly used in the industry, whereby hundreds or even thousands of receivers are placed on the surface or in shallow vertical observation wells above the passive seismic sources (Duncan and Eisner, 2010; Eisner et al., 2011). Surface microseismic monitoring has the advantage of providing wider spatial monitoring aperture and the ability to monitor larger volumes in comparison with downhole monitoring. Furthermore, surface monitoring methods are automatic and there is no need to pick traveltimes manually; on the other hand, the intrinsic signal-to-noise ratio (S/N) for the data recorded by surface arrays is typically low. This makes stacking and coherency-based techniques appropriate choices to detect and monitor passive seismic events recorded by such arrays (Chambers et al., 2010).

Several surface passive seismic monitoring techniques have been developed in the past few years, relying on stacking or coherency analysis; Gajewski et al. (2007) proposed a stacking technique with the back-projection of recorded passive seismic energies. Chambers et al. (2010) developed a monitoring approach so that the stack of passive seismic energies is replaced by the equivalent semblance measure. Grigoli et al. (2013) proposed stacking of short-time average to long-time average ratio traces that are estimated from the raw data. Haldorsen et al. (2013) proposed a coherency-based approach with semblance-weighted deconvolution in the frequency domain.

None of the above monitoring methods is able to overcome polarity variations corresponding to the source mechanism across the moveout curves/surfaces. This is a problematic task in the use of coherency-based surface passive seismic monitoring methods; whereby positive and negative polarities from either side of a source nodal plane result in a complicated radiation pattern in the image domain. To deal with this, several coherency-based monitoring approaches have been introduced that unify/correct polarity variations before monitoring (Gharti et al., 2011; Rodriguez et al., 2012; Chambers et al., 2014; Anikiev et al., 2014; Zhebel and Eisner, 2014). These workflows compute the moment tensor of passive seismic events for polarity corrections followed by coherency-based monitoring/localization, which are typically time-consuming.

To overcome polarity variation task along moveout surfaces, we suggest a coherency-based surface monitoring approach that relies of implementation of semblance on separate clusters of stations followed by averaging the results from all the station clusters. Herein, we present a brief explanation of the suggested workflow and apply it on a semi-synthetic 3D data example generated from a reverse-oblique source at low S/N condition. Since classic coherency-based monitoring workflow is the main imaging framework for several modern monitoring approaches (e.g. Chambers et al., 2014), we compare the results from the suggested workflow with the results from the classic coherency-based technique. The obtained result from the proposed workflow present the true location of the passive seismic source while the result from the classic technique present a null at the true source location.

METHOD

The first stage in our suggested approach includes dividing the subsurface volume into a set of separate image points in the image domain; each of them has the potential to be the location of a passive seismic source. As timing is unknown for passive seismic events, the initial record has to be shifted to make a series of time-delayed-sections corresponding to each potential origin time. Given the velocity field at each image point of the volume, moveout surfaces are estimated for all of the image points. This can be done in both time- and depth- domains. In the classic approach, coherency measurement using semblance (Taner and Coehler, 1969) is performed along the corresponding sliced moveout surfaces for all the image points to achieve time-delayed-images in time/depth domain:

$$S = \frac{\sum_{t=-m}^{m}\left(\sum_{i=1}^{n} f_{it}\right)^2}{n\sum_{t=-m}^{m}\sum_{i=1}^{n} {f_{it}}^2} \qquad (1)$$

where f_{it} is the i_{th} at a given time t within a window of 2 m+1 sample length, and n is the number of considered traces in the searching window. To deal with polarity variations, we suggest dividing the recording stations into separate clusters of stations and implementing semblance analysis along the corresponding sliced moveout surface. Final image function at each image point is achieved by averaging the coherency measures of all station clusters. This process is repeated for the same image point of all time-delayed-sections. Then, the image function is obtained by collapsing all calculated semblance values of all time-delayed-sections to a maximum value. Computation of image function (*IF*) for an image point through the suggested workflow is summarized by

$$IF = MAX\left(\frac{1}{N_g}\sum_{k=1}^{N_g} S_k\right) \qquad (2)$$

where k denotes the cluster of stations and N_g is the number of chosen receiver clusters. Each cluster is considered a 2D subset of a recording arm. To avoid destruction caused by polarity variations, it is important to choose a small number of stations per cluster, which we chose four in this research.

RESULTS

As mentioned in the previous sections, passive seismic events have often polarity variations due to the source mechanism.

The corresponding radiation pattern can be symmetric about the apex of hyperboloid moveout surface. Strike-slip and dip-slip horizontal-slip sources are two examples of passive seismic sources with such radiation pattern. Worst case scenarios happen where the symmetry point in the projected radiation pattern is not at the apex of the hyperboloid. For example, fault plane dip causes radiation pattern asymmetry with respect to the observation surface. To study the performance of the suggested coherency-based monitoring approach in such situation, we modelled an input data set including an event generated from a reverse-oblique source (ROS). We embed the passive seismic source in a constant velocity medium with coordinates of x_s=0 m, y_s=0 m and z_s=500 m. The compressional velocity of the medium (v_p) is set to 1800 m/s. The sampling interval and geophone spacing are chosen 2 ms and 20 m, respectively.

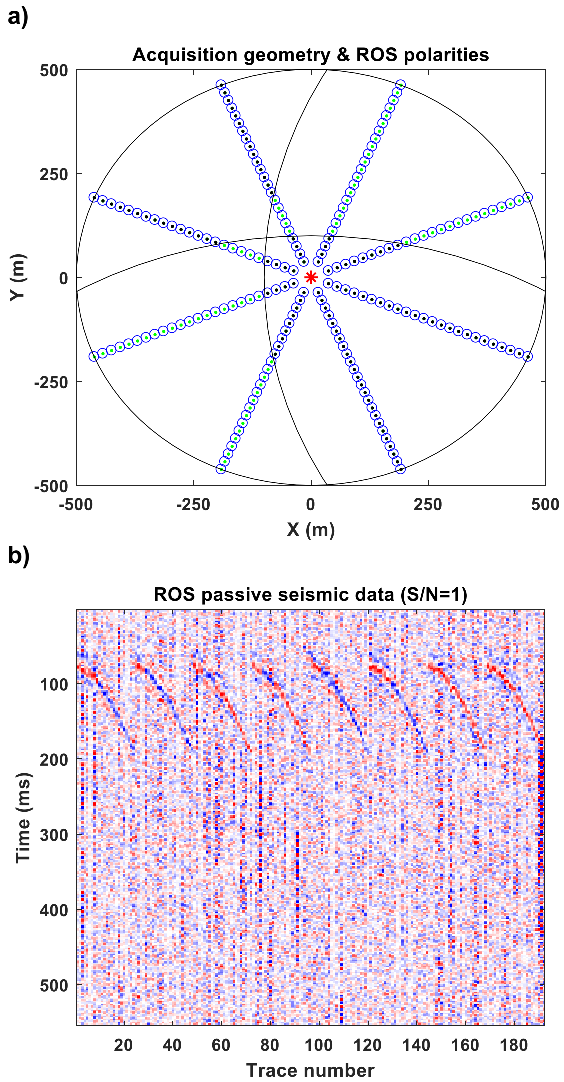

Figure 1. a) Polarity distributions from a reverse-oblique passive seismic source recorded by a star-shaped array where the surface source location, stations, positive and negative polarities are shown by the red star, blue circles, black and green dots, respectively, and b) the corresponding noisy passive seismic record (S/N=1).

Figure 1a illustrates the corresponding star-shaped survey geometry, including 8 recording arms and 192 stations. Blue circles indicate the location of deployed stations. Arrival positive and negative amplitude variations are indicated by black and green dots, respectively. The black circles show the schematic view of reverse-oblique beach ball source radiation pattern. The star-shaped array has a maximum horizontal spread of 500 m from the passive seismic source, equal to the source depth. The subsequent images were constructed using 101×101×280 spatial grids of image points with horizontal spacing of 10 m and vertical spacing of 3.6 m. To demonstrate independence of the technique to the source origin time, we applied a time shift of -0.2 s to all traces of the recorded event. To test the suggested workflow in the presence of realistic noise, we polluted the modelled synthetic data with real noise data, which were collected for seismic imaging using ambient noise (Khoshnavaz et al., 2018), with S/N of 1 (Figure 1b).

We first applied the classic coherency-based monitoring technique on the semi-synthetic data set, to test its performance in the presence of polarity variations. Figure 2a (see the final page) shows the corresponding cross-section image of the monitoring result. One can see a lobed radiation pattern with a null at the true source position, typical of the application of the classic approach to surface passive seismic data sets.

To construct the equivalent image using the proposed approach, we divide 192 recording stations into 48 clusters of stations, each of which includes four neighbouring stations. Figure 2b (see the final page) shows the cross-section image of monitoring result obtained by the application of the suggested approach, indicating the true passive seismic source location. This demonstrates the theoretical concepts of the suggested approach and its better focusing power over the classic coherency-based workflow in the presence of polarity variations.

CONCLUSIONS

Surface passive seismic monitoring plays an important role in the mining and oil-and-gas industry. Low signal-to-noise ratio is an intrinsic character of passive seismic data sets recorded by surface arrays. In such condition, semblance is a powerful tool to search for the coherent events including passive seismic events. Presence of polarity variations due to source mechanism across the moveout surfaces is complicating factor for semblance analysis. To deal with this problem, we proposed a straight-forward coherency-based surface passive seismic monitoring approach that divides the records into separate clusters of stations for semblance analysis. We applied the approach on a semi-synthetic data set generated from a reverse-oblique source. The achieved result demonstrates the capability of the suggested workflow in the presence of polarity reversals and field recorded noise.

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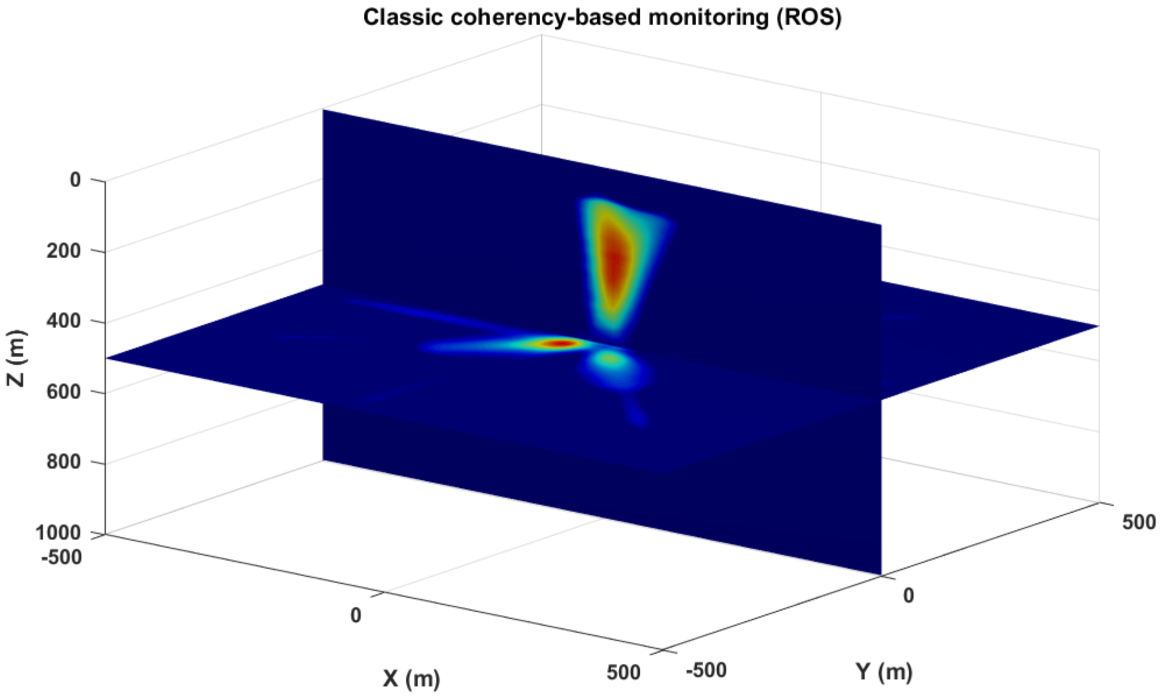
a)



b)

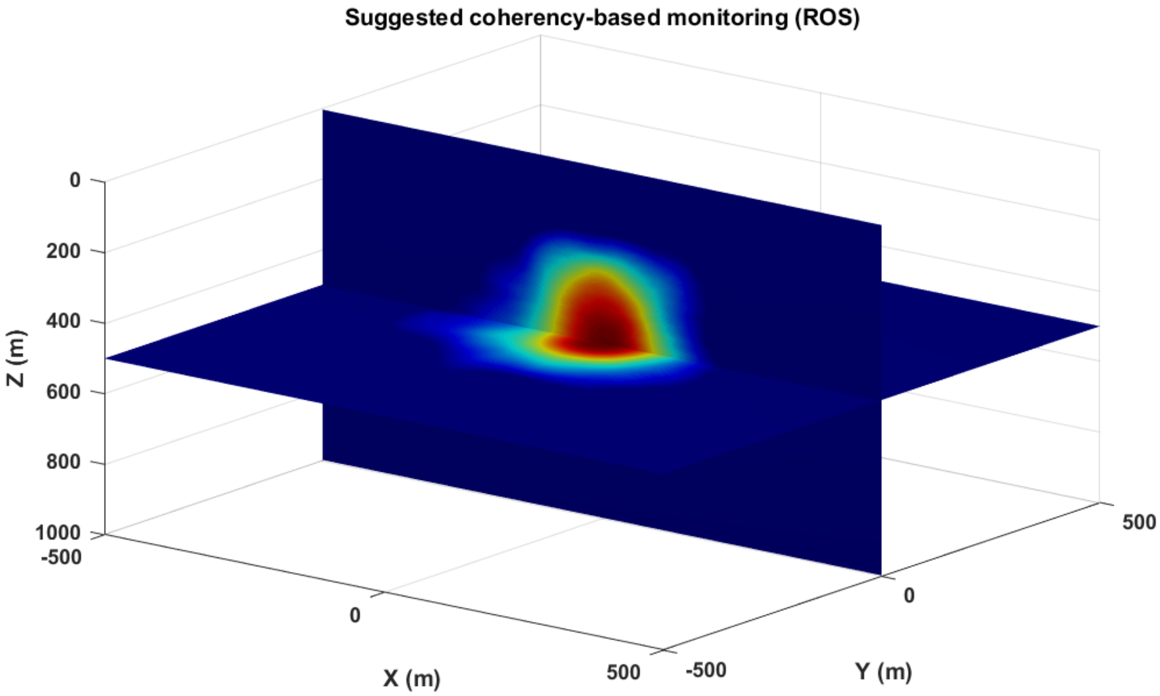


Figure 2. Cross-sections of monitoring results obtained by the application of a) the classic and b) the suggested coherency-based surface passive seismic monitoring techniques.