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Application of Full Wave Location technology with determining seismic moment tensor of events for Hydraulic Fracture Monitoring and Natural Fractures

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SUMMARY
Introduction

In recent years, the problem of determining the parameters of microseismic sources has become especially important. Microseismic monitoring allows continuous monitoring of subsurface state and controlling of physical processes which generate elastic waves, in particular the process of hydraulic fracturing (Rutledge 1998; Urbancic 1999; Urbancic and Maxwell 2002; Shapiro 2015).

This paper about a Full Wave Location (FWL) technology [1] that allows solving an event location problem with determination of its seismic moment, using maximum likelihood method, full wave numerical simulation and optimized survey design. The FWL technology has high noise immunity to correlated surface noises and allows determining orientation of each fracture.

Theory

The focal mechanism of any microseismic event can be characterized by the seismic moment tensor. Aki (1967) Aki, Richards (1980) [2] introduced the concept of seismic moment tensor which depends on the source power and orientation of the medium movement in the source vicinity. The full seismic moment tensor characterizes all possible stresses occurring in the vicinity of the seismic source epicenter. Tensor components $m_{ij}$ are the values of the moments applied along axis $i$ when the points of force application along axis $j$ are displaced. Thus, the seismic moment is the most general characteristic of any seismic event.

In order to reconstruct the seismic moment tensor we propose to use the well-known method of maximum-likelihood estimation (MLE). MLE is widely known in many areas of science and technology, in particular in seismology. Aki, Richards (1980) [2] see it as the method of reconstruction of the magnitude of the earthquake. Their description of MLE involves reconstruction of the sequence of scalar amplitudes in the inferred focus of the earthquake, but not the moment tensor. They compare this method to diffraction stacking in theory and use reconstruction of the Argentinean earthquake focus as an example. They show that the greatest effect of MLE application appears in case of high noise correlation. As an example, they show the case when the surface waves from the Kamchatka earthquake were mixed with ones from the Argentinean earthquake. In this case the reconstruction performed by MLE is better than by diffraction stacking.

In the process of hydraulic fracturing microseismic monitoring or when solving other applied problems, microseismic data usually includes noises of various kinds of surface equipment (fracking equipment, production or fluid injection into the formation in the surrounding wells, etc.) which generate well-correlated periodic noise. This noise is especially noticeable in surface monitoring.

The maximum likelihood method for simultaneous determination of tensor components of a seismic moment of a microseismic event, considering it as an event isolated in space and time. We assume that the noise on sensors can be strongly correlated.

We also assume that all other events, both in the study area and beyond it, according to the central limit theorem, create normally distributed noise on sensors, which is generally correlated.

Let’s assume that we know the Green's functions of each independent components of the seismic moment tensor displacement vectors $s^i(x,y,z,t,x_0,y_0,z_0,t_0)$ (seismic responses) at each point of space, at any specific time. The further discussion is related to a certain selected point in time and space $x_0,y_0,z_0,t_0$ and the given four parameters will be omitted. For numerical calculation, we approximate the delta-function of impact by certain amplitude with duration of one simulation time-step.

In this case the seismic signal from a complex seismic event at each point of space and at each moment of time, but with arbitrary seismic tensor components $m^i$, in compliance with the superposition principle of wave fields in a linear medium, could be written as
Let us examine a set of seismic sensors placed at certain points in space and recording a certain displacement component \((x, y, z)\). Thus, for three-component sensors, in this representation, we have three sensors registering various components located in a single point of space. Let us suppose that we have \(K\) receivers. Then the seismic signal on \(k\)-th \((k = 1..K)\) seismic receiver could be written as (Sipkin 1982):

\[
 z_k(t) = n_k(t) + \sum_i m^i s_k^i(t) \tag{2}
\]

Here \(n_k(t)\) is the noise on \(k\)-th receiver, and \(s_k^i(t)\) is a displacement on \(k\)-th receiver from \(i\)-th elementary microseismic event. Alternatively, in vector form:

\[
 z = n + \sum_i m^i \tag{3}
\]

The problem can be regarded as determining the seismic tensor components \(m^i\) as a problem of finding the maximum likelihood as follows:

\[
 L(m^i) = \exp \left(- (z - \sum_i m^i s^i)^T C^{-1} (z - \sum_i m^i s^i) \right) \tag{4}
\]

By solving this problem are deduced the values of \(m^i\), whereby the likelihood function reaches the maximum.

Thus, is evaluated the maximum plausible value of the seismic moment tensor for a certain point of space at a specific time \(t_0\). By moving a time point \(t_0\) we reconstruct the moment values \(m^i\) for each time point in each point of space. Then is estimated SNR of \(m^i\) [2] in the investigated volume and select only reliable seismic events.

**Field operations**

The observation systems used for HF monitoring consist of three-component broadband CME-4111-LT (Fig. 1, a) or LE-3DLite (Fig. 1, b) seismometers and a Baikal-ACH88 recorder (Fig. 1, c), designed to record the vertical and two horizontal components of seismic vibrations and to convert them into synchronized digital 3C signals.

Self-noises of the CME-4111-LT and LE-3DLite (~3 nm/sec) allow to record low frequency (1-40 Hz) ambient background noises which contain responses of deeper events. These wireless acquisition modules can be applied in severe environment, including warm countries and wintertime.

Observation scheme is designed to maximize signal to noise ratio in the investigated volume. Most sensors are installed in quiet places far from surface sources of noises. In addition, sensors are relocated from topographic anomalies like swamps, rivers, ravines. Usually the average radius of the observation scheme is slightly greater than the depth of the investigated reservoir.

**Full wave numerical simulations**

Parameters of 3D viscoelastic model of medium were taken on the base of vertical seismic profiling velocities and structural seismic data. Then using the finite-element technique the wave processes caused by different types of impact (according to seismic moment tensor components) are simulated at the depth of the reservoir in the investigation volume.

During this process the full-wave responses are recorded in the places of sensors deployment. Those responses are the full form of seismic waves from an event, including P, S, exchanged waves, re-reflected waves and other by three components.
Figure 1 The scheme of sensors deployment for hydraulic fracture monitoring on the depth of 2400 m (left), right: the view of «CME-4111-LT» (a), LE-3Dlite (b) seismometers and «Baykal-ACH88» recorder (c).

Examples

The figure 2 shows the example of Full Wave Location technology application for Natural Fractures Network Mapping (a) and Hydraulic Fracture Monitoring (b).

The results of natural fractures network mapping were obtained on the base of two-week long records of microseismic noises before the hydraulic fracturing. There were detected events only with high reliability, then was calculated the azimuth of fractures. The rose of natural fractures' directions was stacked.

The red zones in the eastern part of figure 2(a) were associated with seismic emission of field production from the neighbor eastern horizontal well.

Then was conducted the monitoring of hydraulic fracturing. Seismic events were detected during each stage of hydraulic fracturing, then was determined the azimuth of fractures for located seismic events. Figure 2(b) presents the stacked results of all monitored stages. The rose of natural fractures' directions was stacked. Axial lines of fractures directions were obtained using dynamic analysis of events'
appearance. Axial line colors correspond to different hydraulic fracturing stages. As you can see, the axial lines are the same for some stages.

The axial lines from hydraulic fracturing were overlaid on natural fractures' network map (fig.2, a). As you can see, axial lines of hydraulic fractures mostly have the same orientation as natural fractures. Based on that fact, it is possible to forecast fracture directions before the process of hydraulic fracturing. Natural fractures' network mapping should be carried out before designing a horizontal well in order to achieve maximum productivity.

**Figure 2** a) The final stacked map of microseismic activity for all stages (1, 3-7). Oriented segments are azimuthal orientations of fractures that generate seismic events. Colored bold lines are axial lines of fractures' directions by stages. b) Map of natural fractures' network. The colored map is the stacked microseismic activity. The small oriented segments are local azimuths of fractures' activity. Colored bold lines are axial lines of fractures' directions by stages.

**Conclusions**

The Full Wave Location technology is a combination of maximum likelihood method, full-wave numerical simulation, high sensitive sensors application and optimized survey design. The advantages of this location technology:

1. The location uses the full shape of seismic wave from an event, including P, S, exchanged waves, re-reflected waves and others by 3 components;
2. The location technique can reduce the impact of correlated noise and its level.
3. It is possible to locate events with signal to noise ratio of about 1/100 on sensors [1];

Results of FWL technique application show that this technology is applicable for hydraulic fracture monitoring at about 2400 m depth. The FWL technique can be applied for determination of fractures' development during hydraulic fracturing, optimal design of horizontal well and for efficient field development.

**References**