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Influence of the Double-couple Source Model on the Sensitivity of Microseismic Monitoring Networks

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SUMMARY

Microseismic monitoring has significant interest of researchers as well as operators of the hydraulic stimulations or material extractions. It is necessary for the successful monitoring to design the monitoring network in order to be able to locate seismic events above certain threshold of magnitude with sufficient accuracy. The detection threshold becomes more complicated if one considers double-couple (shear) source mechanism therefore the average values of the radiation pattern of the source are widely used. In this study we are illustrating how the double-couple source radiation can be included in network design. We discuss influence of the three main classes of mechanisms: strike-slip source mechanisms, normal (reverse) faulting mechanisms and unknown orientation of the source mechanisms. The specific sensitivity distributions are computed by the empirical relationships for the surface network of 4 stations and for single borehole array. These simulations showed, that the radiation pattern of the seismic sources can have large influence on the sensitivity of the monitoring networks (especially limited networks like surface network of 4 stations or single borehole array). We showed also the influence of the unknown orientation of the source mechanisms sensitivities compared with the sensitivities computed by using average values of the radiation pattern.

Introduction

Microseismic monitoring attracted significant interest of researchers as well as operators of the hydraulic stimulations or material extractions. It is necessary for the successful monitoring to design the monitoring network in order to be able to locate seismic events above certain threshold of magnitude with sufficient accuracy. Furthermore, the network design plays a crucial part in detectability of seismic events in a certain region. Traditionally monitoring network designs are evaluated based on arrival times and noise levels (e.g., Raymer and Leslie 2011, Zimmer 2011). Even greater challenge is faced when one attempts to estimate the detectable magnitude of the microseismic events that can be induced by hydraulic injection. This challenge is met through various means ranging from seismic modelling in the anticipated source regions obtained in the geomechanical analysis (Maxwell et al. 2003), through calibration shots (Waldron et al. 2010) or empirical relationships (Hallo 2012, Freudenreich et al. 2012).

Nearly all previous studies focus on estimation of the detectable magnitude of the induced events neglecting radiation pattern. It is known that the radiation pattern cause variation of amplitude on the order of 10 to 100 on receivers in the vicinity of the source. As a result the detection threshold becomes more complicated if one considers double-couple (shear) source mechanism therefore the average values of the radiation pattern of the source are widely used. In this study we are illustrating how the double-couple source radiation can be included in network design and that it can have large influence on the sensitivity of the monitoring networks. We show how this sensitivity can be modeled and compare to previously used methods. We illustrate that source radiation especially influences design of limited networks (e.g., surface network of 4 stations, or single borehole array).

Method

In this study we use the sensitivity of a monitoring network (or array) determined as the smallest reliably detectable magnitude. Such magnitude can be determined as the minimal magnitude of a double-couple source in a spatial point, from which the arrivals of (e.g., direct) wave amplitudes on receivers are above a triggering threshold. The threshold for size of these amplitudes depends on the detection method and it is usually a multiple of the background noise level (e.g., Freunderich et al. 2012). In this study we use the moment magnitude M_w (Kanamori 1977):

$$M_w = \frac{2}{3}(\log_{10}(M_0) - 9.1). \quad (1)$$

The seismic moment M_0 [Nm] can be calculated from the expressions for far-field displacement at receivers in a homogeneous medium (Aki and Richards 1980, Chapter 4.5 - The radiation pattern of body waves). The time derivative of such expressions leads to equation for the seismic moment in a homogenous isotropic medium dependent on the far-field ground motion, source radiation pattern and the parameters of the medium:

$$M_0 = \frac{4\pi\rho c^3 r \Omega_0}{U_\Theta}. \quad (2)$$

Here r is distance from the source [m], ρ is medium density [kg/m³], c is the wave velocity [m/s] and U_Θ is the radiation pattern. The term Ω_0 is low frequency limit of amplitude far-field spectrum from the particle displacement for ω -square source model (Aki and Richards 1980, Chapter 14.1 – Kinematics of an earthquake as seen at far field). Where ω -square source model give satisfactory results for frequencies higher than 1 Hz. Equation (2) also shows that the low frequency limits of the amplitude far-field spectrum are different for the P- and S-waves for the same values of seismic moment, density and distance from the source. Then overall level of the Ω_0 in the monitored volume is smaller for the P-waves, because of the higher wave velocity c . Therefore the sensitivity of monitoring networks for P-waves is weaker than for S-waves. The radiation patterns U_Θ for P, SV and SH waves are expressed as functions of strike, dip, rake, source-receiver azimuth and take-off angle (Aki and Richards 1980, Chapter 4.5 - The radiation pattern of body waves), as

$$U_{\Theta i} = M_{jk} G_{ij,k}. \quad (3)$$

Here M_{jk} is the moment tensor and $G_{ij,k}$ is the derivative along k -th direction of Green's function.

Detection of an earthquake may be subject to somewhat subjective criteria: we may require detection of both P and S-waves on several (e.g., at least three) receivers or perhaps detection certain number of P-wave and S-waves across the monitoring network. Due to the fact that P-wave radiation is much weaker usually the limiting criteria is the number of P-wave detections required on a network. This is particularly limiting on small networks of a few receivers monitoring local seismicity.

Strike-slip source mechanisms

The strike-slip sources are very common for natural seismicity as well as for micro-seismic events triggered by hydraulic stimulations (Rutledge and Phillips 2003). These sources are caused by a horizontal motion on a vertical fault plane resulting in two perpendicular vertical nodal planes. For example, a local surface monitoring network consisting of a few receivers is less likely to detect the strike-slip sources with nodal planes intersecting two or more receivers. Specifically there will be at least two receivers with no P-wave arrivals for some sources (Fig. 1 – Left panel versus central panel). The situation is even worse for the simple downhole vertical monitoring arrays (Fig. 1 – Right panel). Because of the vertical orientation of the both nodal planes, there are source positions in four mutually perpendicular directions from the monitoring array where no P-wave arrivals on all receivers are detectable in the whole array. An example of real case study influenced by this is discussed by Fischer et al. (2008). Special cases are source positions just above or below such array where no P-wave arrivals on all receivers are detectable and also S-waves have reduced amplitudes. Monitoring networks with receivers in multiple azimuths an offset such as buried arrays and star-like arrays (Duncan and Eisner 2010) usually do not have limitation on detectability resulting from the source mechanism radiation, due to variable azimuths between receivers. But even for these arrays there are favourable and unfavourable directions of strikes especially if they are laid out on a regular grid.

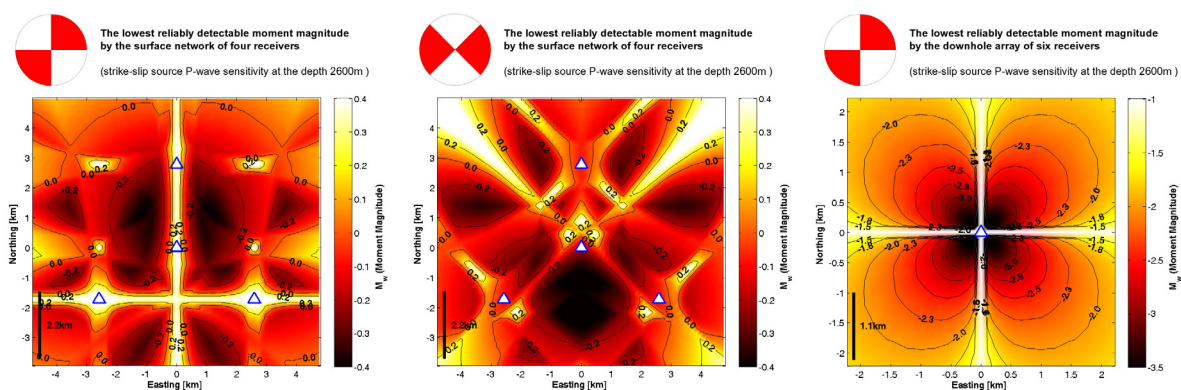


Figure 1 Distribution of the sensitivity for strike-slip sources (P-wave sensitivity). Sensitivity is shown in color scale and position of the receivers is highlighted by blue-white triangles. There are horizontal slices at the depth 2600m for different strike of the strike-slips in two different monitoring arrays in the panels. Left & center panels – Triangular surface network of four receivers. Right panel – Downhole array of six receivers placed in depth range 2350 to 2850 meters. Homogeneous medium with P-wave velocity = 4300 m/s; density = 2600 kg/m³; $Q_p = 100$. Noise level is set to 100 nm/s for surface network and 5 nm/s for downhole array in these tests.

Normal (reverse) faulting mechanisms

The normal faulting sources affect the sensitivity distribution in the different way than strike-slip sources. The nodal planes are not vertical and then the sensitivity depends more on vertical distance between earthquakes and the receivers. Local surface monitoring network consisting of a few receivers is less likely to detect the normal faulting sources with strikes parallel to direction between two or more receivers. Specifically there will be at least two receivers with no P-wave arrivals for some sources. Such source positions are not below the line connecting the receivers (like in the case

of strike-slip sources), but they are located on the two dipping planes intersecting the receivers (Fig. 2 – Left panel, source positions with easting 2.5 km or -2.5 km). In case of the strikes different than direction between two receivers there is an unfavourable distance between these receivers for specific depth of sources (no P-wave detection by them; Fig. 2 – Left panel, source positions with easting 0.0 km). If we assume normal (or reverse) faulting source with fault plane dipping at the dip δ at the depth d under the surface monitoring network, then we can express the unfavourable distance between two surface receivers like:

$$h_{surf} = \frac{2d}{\sin(2\delta) \cdot \sin(\alpha)} \quad (4)$$

α is the smallest angle between the strike and the direction between two receivers and h_{surf} is the resulting unfavourable distance for monitoring of the sources in the depth d . We note that equation (4) for unfavourable distance between two receivers with $\alpha = 90^\circ$ and $\delta = 45^\circ$ for such source model has the same form like formula for common recommended maximal distance between two receivers (Hallo 2012). The normal faulting sources have better detectability on downhole arrays than strike-slip sources (unless these arrays are horizontal). Weaker detectability is registered only at greater distances from the array in the directions parallel to the strike (Fig. 2 – Right panel).

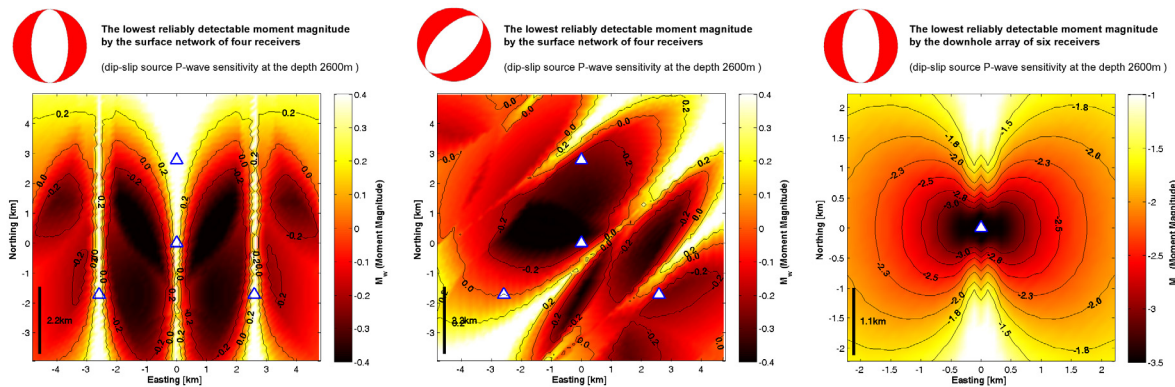


Figure 2 Distribution of the sensitivity for normal faulting sources (P-wave sensitivity). Sensitivity is shown in colour scale and position of the receivers is highlighted by blue-white triangles. There are horizontal slices at the depth 2600m for different strike of the normal faulting sources in two different monitoring arrays in the panels. Left & center panels – Triangular surface network of four receivers. Right panel – Downhole array of six receivers placed in depth range 2350 to 2850 meters. Homogeneous medium with P-wave velocity = 4300 m/s; density = 2600 kg/m³; $Q_p = 100$. Noise level is set to 100 nm/s for surface network and 5 nm/s for downhole array in these tests.

Unknown orientation of the source mechanisms

Sensitivity of the monitoring networks in the local conditions with unknown orientation of the source mechanisms is usually calculated with the average values of the radiation pattern (e.g., 0.52 for P-waves and 0.63 for S-waves). We tested the influence of the unknown orientation of the source mechanisms by computing sensitivity of the monitoring networks for extensive set of different source models with the parameters from range: 0° to 360° strike, 0° to 90° dip, -180° to 180° rake. In such case is sensitivity described for a certain threshold value of percentage of detectable mechanisms from all tested mechanisms. The sensitivity is then weakest sensitivity from the selected percentage of the tested mechanisms, where the most favorable mechanisms are included into selection. The most interesting result is that sensitivity computed with the threshold of 50% in the definition above and average P- and S-wave radiation values are almost the same. It means that if the sensitivity was computed by using average values, there will be 50% of all possible source model orientations detectable with equal or better sensitivity than computed one. The sensitivity for different thresholds can be computed for exact network geometry by simulations with variable orientation of source mechanisms. Such sensitivity is systematically worse than the one computed from average values of the radiation pattern for higher percentage than 50% and better for lower percentage. The gradation of

this increase/decrease of the sensitivity is much more significant for small surface networks and downhole arrays than for more extensive monitoring networks.

Conclusions

The simulations with different double-couple sources showed, that the radiation pattern of the seismic sources can have significant influence on the sensitivity of the local monitoring networks and arrays (especially on the smaller or spatially constrained arrays). The sensitivity is influenced mostly by the P-waves sensitivity because the overall amplitudes of far-field spectrum for the P-waves are smaller than for S-waves and the radiation pattern of the P-waves is also more limited than the S-wave radiation pattern. Strike-slip sources have two perpendicular horizontal directions with zero P-wave radiation intersecting Earth's surface. If there are more receivers in line of such direction, the sensitivity will be reduced for some source positions because of decrease of the number of the stations with P-wave arrival. The normal or reverse faulting sources affects the sensitivity distribution in the different way than strike-slip sources. Sensitivity is more influenced by the relative horizontal and vertical distance among receivers and possible source positions. For the events outside the network, the P-wave radiation affects sensitivity especially in the directions along the strike. We tested also the influence of the unknown orientation of the source mechanisms and compared results with the sensitivities computed by using average values of the radiation pattern. These sensitivities are similar if the threshold is set to 50% of all possible source model orientations detectable with equal or better sensitivity than computed one.

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