

P021

Microseismic Surface Monitoring Network Design - Sensitivity and Accuracy

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SUMMARY

How to design a seismic network for monitoring seismicity in the vicinity of a reservoir and achieve the highest sensitivity and accuracy? What is the smallest earthquake you can detect with a given seismic network? How to design a seismic network when you want to distinguish between induced and natural earthquake?

Numerical simulations are done to answer these questions. Simulation results are presented as depth slices of the minimum detectable earthquake magnitude or as depth slices of the accuracy of an earthquake location. Simulations with various network geometries helped us to draw simple rules for the optimal surface monitoring network.

Introduction

Microseismic monitoring has gained significant interest in the last decade from academic as well as applied researchers. However, the lack of knowledge of where the seismic events will occur brings a significant challenge of designing the monitoring network to monitor all area of interest. Therefore, network design of monitoring networks for microseismic monitoring plays important role in successful operations (e.g. Raymer and Leslie, 2011). The network planning is even more challenging in seismic monitoring for significant (felt) seismicity in the vicinity of oil and gas reservoirs (e.g. Suckdale, 2010). The monitoring of large events in the vicinity of the reservoirs needs to be carried over significantly larger areas than microseismic monitoring and is usually done from a few (usually less than 10) surface stations.

Method

Sensitivity of a monitoring network can be studied via the smallest reliably detectable magnitude (i.e. magnitude above which our seismic catalogue is complete for a given area). The magnitude is expressed as function of position of receivers in space, level of background seismic noise, frequency of expected signal, the velocity model of medium, quality factor Q_p and density ρ . In this study we use the moment magnitude M_w (Kanamori, 1977):

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

where the moment tensor M_0 [Nm] can be calculated in a homogenous isotropic medium from:

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

where r is distance from the source [m], ρ is 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 spectrum from particle displacement. This factor is determined for minimum signal to noise ratio (SNR) necessary for reliable picking and it can be expressed as function of frequency, amplitude of noise and attenuation. In this study we use $f = 10$ Hz because we can use frequencies up 10 Hz to locate local microseismic events. The representative amplitude of noise $A_{\text{noise}} = 5$ nm/s (at 10Hz signal) is taken from noise measurement in an oilfield (Eisner et. al., 2011). The quality factors for the P and S waves are approximately $Q_p = 100$ and $Q_s = 50$, respectively (Walls et al., 2006).

Locations of seismic events are mostly limited by arrival time reading error, velocity model and inappropriate geometry of the monitoring network. To model these effects we evaluate location uncertainty estimated from misfit of the arrival times and synthetic times and called it a probability density function (PDF) (Tarantola, 1987, Eisner et. al., 2010). PDF can be characterized by an average value and standard deviation from this value σ . Confidence intervals of accuracy $|\pm 2\sigma|$ (95% of location occurrence probability) are then defined for 3 directions (main, secondary, depth) and we define ellipsoidal error with length of the semi-axis of error ellipses (2σ). Accuracy of the events location can be expressed for every point of medium by the length of semi-major and semi-minor axis of the error ellipse and the standard deviation in depth. These uncertainties can be found by many advanced grid search location programs. In our tests, the synthetic events are placed at the slices of interest (with computed arrival times).

Sensitivity of seismic networks

We test several different network geometries to better understand the relationship between the detectability and receivers placement. The detectability can be evaluated by mapping of lowest reliably detectable magnitude in the volume of interest, subject to condition that SNR must be higher than 2.0 for in at least three receivers.

The first experiment is computed for seismic network of 3 receivers for the P-wave amplitudes in homogeneous medium with P-wave velocity 4300 m/s and density 2300 kg/m³ (Figure 1). It is sufficient to use the condition for detection of only P-wave because P-wave amplitude is usually smaller than S-wave amplitude. The simplest geometry of the stations placement is equilateral triangle as shown in Figure 1 – left panel). The sensitivity of this geometry is highest (lowest detectable magnitude) in the center of stations triangle, where the distance from three proximate receivers is smallest, while outside the aperture or at greater depths detectability is controlled by distance and attenuation. In case of more stations, the sensitivity highly depends on the position of additional stations. For example, one more station inside the equilateral horizontal triangle improves the sensitivity inside and also outside of the network. Extension of the network to square geometry does not significantly improve the sensitivity but, on the other hand, it can improve accuracy of location.

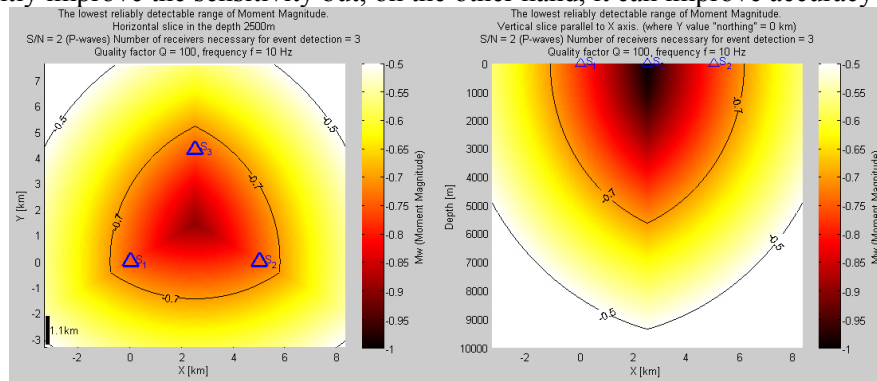


Figure 1 Sensitivity of the seismic network of 3 stations expressed by the lowest reliably detectable moment magnitude in the homogeneous medium with P-wave velocity 4300 m/s and density 2300 kg/m³. Left panel – horizontal slice; right panel – vertical slice.

Accuracy of location depth

The location accuracy in the depth depends mainly on the incidence angle of the ray. The second most important parameter governing the accuracy is the distance between receiver and event. Let the distance be constant, then the smaller the incidence angle is, the higher is the location accuracy in depth. In the next part we study the optimum spacing between receivers on the free surface in terms on location accuracy (the best accuracy in depth with the smallest number of receivers). The optimum spacing depends on requirements, such as good coverage of a horizontal plane and its vicinity in a certain depth. In some cases the optimum spacing for horizontal location or detection (sensitivity) must be even smaller than that for satisfactory accuracy in depth, for example if very high sensitivity is required.

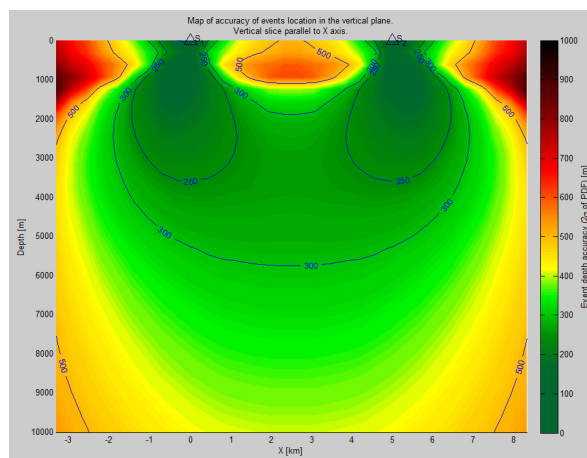


Figure 2 Accuracy of the event location in the depth on the line between two stations of an equilateral triangle (spacing of receivers is 5km, see Figure 1 left panel). The medium is homogeneous half space with P-wave velocity 4300 m/s and density 2300 kg/m³.

Optimal spacing D_{rec} for the location accuracy in depth can be approximated by an empirical rule $D_{\text{rec}} \approx 2 \cdot \text{depth}_{\text{min}}$, where D_{rec} is optimal spacing of receivers and $\text{depth}_{\text{min}}$ is minimum depth of volume of interest. Below the minimum depth, the accuracy of the location in depth is relatively high and quite stable decreasing slightly with depth due to distance from receivers. On the other hand accuracy becomes rapidly worse above this depth for the locations in the centre line between the stations. Example shown in Figure 2 depicts accuracy of location in depth plot on a vertical slice connecting two receivers in equilateral triangle (see Figure 1 left panel). Depth of interest in this test is higher than 2.5km, hence optimal spacing of receivers is 5km.

Accuracy of location in horizontal direction

The location accuracy in the horizontal direction is mainly controlled by geometry of the surface receivers. The location error ellipse major semi-axis of uncertainty mainly depends on the „azimuth gap“. The „azimuth gap“ (the largest of all angles among the lines connecting a potential epicenter and every station used to locate the event) should be as small as possible (ideally below 200 degrees according to Havskov and Alguacil (2002) or 180 degrees according to Trnkoczy et. al. (2002)). The second most important parameter governing the horizontal location accuracy is distance among receivers and event location.

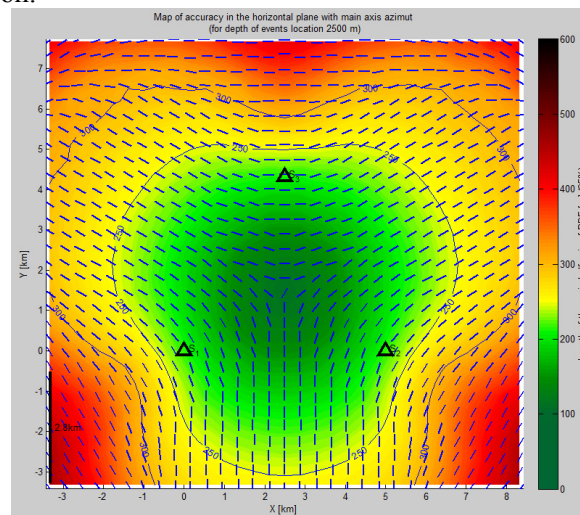


Figure 3 Horizontal slice of accuracy of the events location in the horizontal direction in the depth of 2.5 km (stations in the equilateral triangle) for homogeneous half space with P-wave velocity 4300 m/s and density 2300 kg/m³. Small blue lines indicate main axis azimuth of error ellipses.

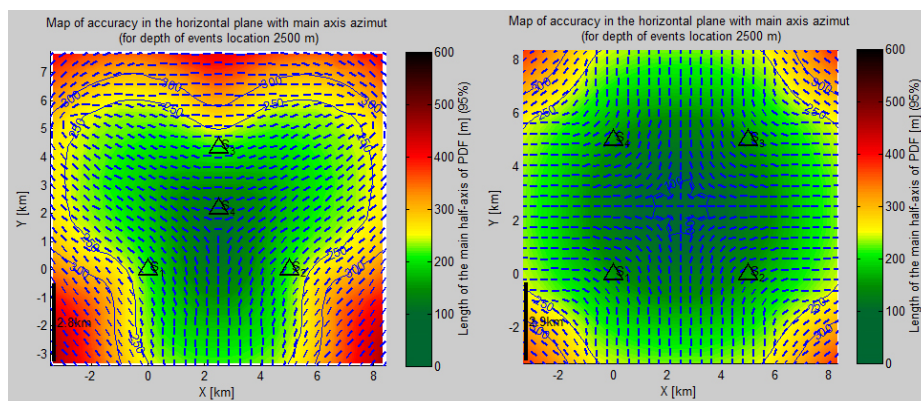


Figure 4 Horizontal slices of accuracy of the events location in the horizontal direction in the depth 2.5 km for homogeneous half-space with P-wave velocity 4300 m/s and density 2300 kg/m³. Left panel – 4 stations in the geometry of triangle with one station close to centre (not exactly in the centre); right panel – 4 stations in square.

The accuracy of location for stations deployed in equilateral triangle on the free surface is shown in Figure 3. The best accuracy is achieved in the centre of triangle, where the „azimuth gap“ is smallest. The uncertainty of location inside the network is approximately circular. Generally, the further from the triangle centre, the lower the accuracy is, while the decline is significantly higher in the direction outside from centre of the network through the stations (caused by increasing of „azimuth gap“). An additional station inside the network (Figure 4 left panel) improves sensitivity and accuracy of location in depth. However, it cannot significantly change accuracy of event horizontal location for events outside of the network because of no change of „azimuth gap“. On the other hand, transforming of the network to square geometry extends the area of good coverage thanks to decreasing „azimuth gap“; it does not improve the sensitivity, though.

Conclusions

Optimum geometry of the local seismic monitoring network depends on purpose of this network. Networks with high demands on sensitivity should have small spacing among receivers, but sufficient coverage. Geometry of the networks with high demands on sensitivity as well as accuracy of events locations has to be determined primarily based on the depth and volume of interest. In such case receiver spacing should not be larger than twice the minimum depth of the volume of interest. For surface monitoring of seismic activity during operations in a single vertical borehole, the simplest recommended geometry is four stations deployed in equilateral triangle with the central receiver close to wellhead.

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