Using Multiple Downhole VSP Arrays for Monitoring and Locating Passive Microseisms in the Oil Reservoirs*

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Abstract

Using a classical hypocenter location method, which depends only on the first arrival times, the uncertainties of the hypocenter location as determined by a microseismic monitoring network composed of multiple VSP downhole geophone arrays in the surrounding wells is calculated. Error analysis illustrates that if the multiple arrays are properly designed, the events recorded by this kind of monitoring network can be located at an accuracy of 5-10 m in the areas between the arrays. Compared to the well-used single-VSP monitoring array method, which needs the combination of azimuths, angles of inclination, and differences between P- and S- arrivals, the multiple downhole VSP arrays method has the advantages of being convenient, reliable and more accurate in hypocenter location.

Introduction

The monitoring and location procedures of passive microseisms occurring in oil reservoirs are generally accomplished by using a single-VSP technique. In principle, a 3-C geophone array allows the location of a microseismic event, where the direction of the event is generally derived from a hodogram analysis of the P-wave first arrivals, and the distance from the P-S arrival time differences (Oye and Roth, 2003). The uncertainty of hypocenter location determined by using this method is generally on the order of tens of meters and often needs many additional conditions to be met (Fabriol, 2001; Phillips et al., 1998; Rutledge et al., 1998). In addition, the determination of the azimuth and angle of inclination of an event from hodograms is often inaccurate and time consuming. Further, picking of the ambiguous P- and S-arrivals is problematic and can cause large error to the microseismic images.

Hypocenter location using only P- and/or S-arrivals has long been used in earthquake research, and is confirmed to be much more accurate than methods using a combination of azimuths, angles of inclination, and differences between P- and S- arrivals. Due to the special straight-line geometry of a downhole single-VSP array, hypocenter location using arrival times only is generally not available. In recent years, with the development of techniques and the need for installation of multiple downhole geophone arrays, the location method using a combination of several single-VSP arrays in surrounding wells became more available. To examine the uncertainty of hypocenter location using P- and/or S-

arrivals only, an error analysis is completed in this study, which provides the horizontal and vertical uncertainties of hypocenter location in a 3-D spatial grid.

Methodology

To determine the uncertainty of the location, an error ellipsoid is generally calculated to depict the error distribution. The error ellipsoid computation is based on the theory of Flinn (1965) and Evernden (1969). This method has been widely adopted by many well-used hypocenter location algorithms like HYPOINVERSE (e.g. Klein, 1978).

Based on this theory, the points $\theta_p(x_p,y_p,z_p,t_{0p})$ on the p% confidence ellipsoid for the solution $\theta_e(x_e,y_e,z_e,t_{0e})$ are obtained from the equation

$$(\theta_p-\theta_e)^T Q(\theta_p-\theta_e) \leq k_p^2$$

where Q is the parameter covariance matrix, and is derived from $Q=(A^TA)^{-1}$. A is the N x 4 matrix of partial derivatives of t with respect to the four components of $\theta_e(x_e,y_e,z_e,t_{0e})$ at final iteration of a least-squares hypocenter location procedure. N is the number of geophones. The confidence coefficient k_p^2 is expressed by $4s^2F(p;4,N-4)$ (Draper and Smith, 1966; Rowlett and Forsyth, 1984), where F(p;4,N-4) is the F distribution with 4 and N-4 degrees of freedom at the p% confidence level. The variance factor, s^2, is an estimate of the picking error of arrivals of seismic phases. The semi-axes of the error ellipsoid are obtained from the eigenvalues of Q by using the singular value decomposition method. Hence, $R_i^{semi}=(2s^2 eigenvalue_i F(p;4,N-4))^{1/2}$.

Numerical Experiments

The one-standard error (68%) ellipses of locations are calculated at the nodes of a 3-D grid. For convenience in viewing the results, the maximum horizontal and vertical errors of an error ellipse are plotted as contour maps on a series of 2-D horizontal cross sections (Figure 1a). The top level of an assumed original VSP array is selected as the zero depth of the 3-D grid. The pre-conditions of the numerical experiments are as follows:

- A constant velocity model (V_p=4000 m/s)
- The picking error of the P-arrivals (s_i, i=1 to N) is a step function of the distance between an event to the geophone ranging from 0.001-0.004sec
- Events are recorded and picked at each station
- Events on the nodes of the grid are relocated to their original positions

Case 1: Three VSPs

In some cases, events can be recorded and located by a network composed of three or more VSP geophone arrays. Suppose a case of three

identical VSP arrays with lateral distances between the original VSP geophone array and the two newly added ones are 400 m east and 400 m north respectively (Figure 1a). Figures 1b and 1c show the horizontal and vertical distributions of the one-standard location errors on four horizontal cross sections for depth levels of 0, 20, 40 and 60 m. Due to the symmetry of the error distribution, the cross sections below the middle level of the geophone arrays are not shown. The major features of the distributions of the horizontal errors are: errors are only 5 m in most areas between the wells, and less than 10 m between the arrays. There is no significant change of the patterns within the range of the vertical aperture of the VSP wells. Outside the frame, errors increase gradually with the epicenter distance. Vertical errors can also be located in a good accuracy of 5-10 m in most areas within the frame of the network throughout the vertical aperture. This uncertainty is considerably lower than those derived from the well-used single-VSP location method.

Case 2: One VSP + Multiple Geophone Receivers

With respect to the availability of VSP wells, a single-VSP geophone array is the most common case. Installation of geophones on the surface is a fast and cost-efficient selection to form a 3-D monitoring network. However, the microseismic events induced by the fracturing process are generally too weak to be detected at the surface as discrete events. Deploying several downhole geophones at shallow depth in surrounding wells may be a cost-efficient and applicable approach not only for detecting the weak events but also for forming a 3-D monitoring network for the application of the arrival time only location method. We calculated the error distribution of cases when networks with the newly added geophones at levels of 0, 1 and 2 times the original VSP vertical aperture above the top geophone of the VSP array (Figure 2).

The horizontal and vertical location errors with a vertical gap of twice the VSP vertical aperture are illustrated in Figures 2b and 2c. From the error distributions, horizontal errors are determined to be less than 5m near the original VSP array. The radius of the 10 m-contour surrounding the VSP array is approximately 2/3 the distance between the VSP well and any of the newly added geophones in all horizontal cross sections. The horizontal location error is less than 20 m almost within the whole frame of the network. This means that this combination of geophones with an existing VSP geophone array can be used to monitor the microseismicity in the areas close to the VSP array at a good accuracy. The vertical location errors near the VSP well can be located to an accuracy of 5 to 10 m. Within the frame of the network, the vertical error is less than 20 m throughout most of the area. In addition, the relationship between the gap of the levels of newly added geophones and the original VSP are examined by calculating the error distributions of different cases. Nothing obvious distinguishes between the cases with gaps of 0, 1 and 2 times of the vertical apertures. Thus, from the geometrical point of view, we conclude that it is not a necessity to drill the surrounding wells deep enough to install geophones close to the top level of the original VSP well. Obviously, drilling shallow surrounding wells can be fast and cost-efficient. However, as the proximity of the newly-added geophones to the VSP level is crucial to the signal quality, both factors must be considered simultaneously before deciding on the drilling depths of the surrounding wells for the installation of the newly-added geophones.

Conclusions

- A microseismic monitoring network composed of three or more VSP arrays can reduce both the horizontal and vertical location uncertainties to an accuracy of 5-10 m within the frame of the network.

- Within the vertical aperture of an existing VSP, the effect of the depth of newly added geophones in the surrounding wells appears insignificant to the uncertainties of location.
- A network composed of a VSP array and several geophones in the surrounding wells can reduce location errors to 5-10 m for most areas within the frame of the network.
- The multiple VSP array method is convenient, reliable and more accurate than the well-used single-VSP location method.

Acknowledgements

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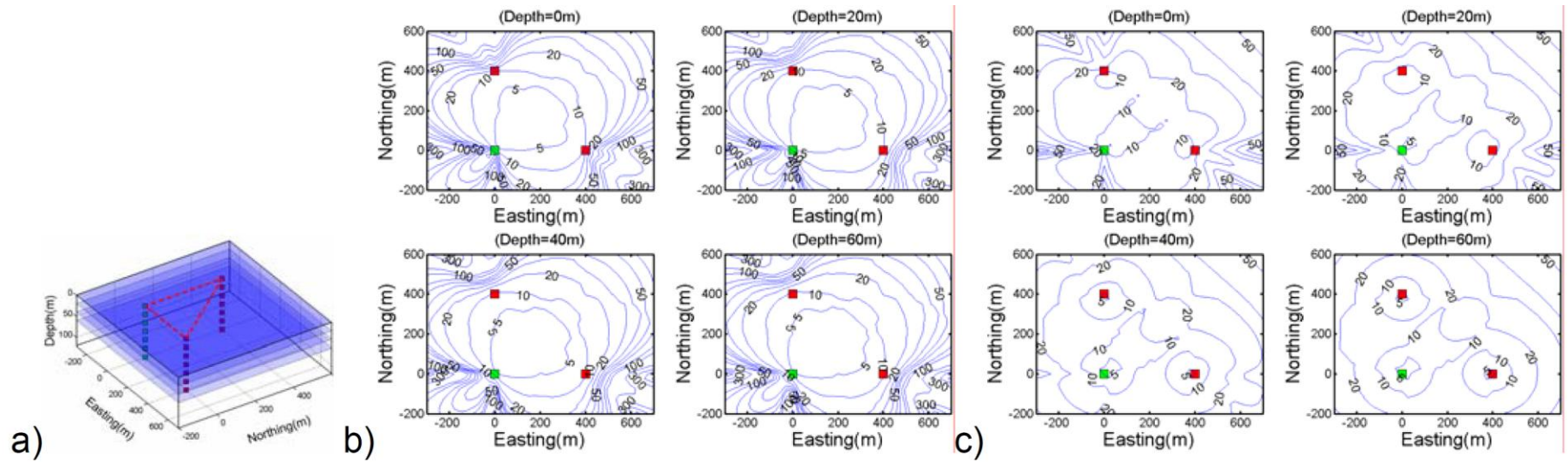
Figure 1. (a) Illustration of the original VSP array (green squares) and two newly added VSP arrays (red squares). Each VSP array is composed of seven geophones with a vertical spacing of 20 m. Red dashed lines connecting the VSP wells define the frame of the network. (b) Contour maps of the horizontal location error. Depths of the horizontal profiles are marked on the top of each diagram. (c) Contour maps of the vertical location error. Similar to Fig.1b.
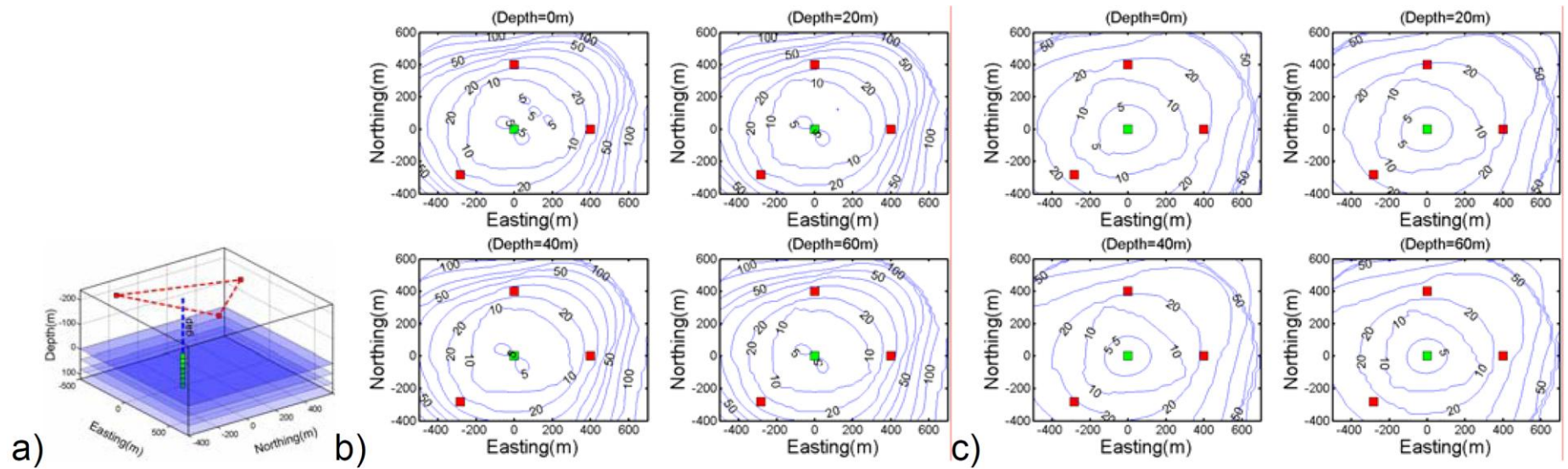
Figure 2. (a) Illustration of the original VSP array (green squares) and three newly added geophones in three surrounding wells (red squares). The vertical gap between the top-level geophone of the original VSP array and the newly added geophones (blue dashed line) is two times of the vertical aperture of the original VSP array. Red dashed lines connecting the surrounding wells define the frame of the network. (b) Contour maps of the horizontal location error. (c) Contour maps of the vertical location error.