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OPTIMIZING RESOURCES

Feasibility Study of Simulated Annealing Inversion Method in Fracture Detection with Tiltmeters

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Summary

Tiltmeters can be used to obtain ground deformation caused by hydraulic fracturing and further to inverse subsurface fracture parameters. A new inversion approach based on Simulated Annealing (SA) algorithm has been proposed for its significantly larger convergent region compared with conventional ones. However, in fracture mapping experiences, the measured signal might be weak and disturbance due to environmental noises, inappropriate deployment configuration or instrumental error. In such cases, the SA approach may fail in obtaining accurate fracture parameters. To rule out these problems, we conduct a series of synthetic tests to obtain an applicable deployment configuration of tiltmeters as well as the effective range of signal-to-noise ratio (SNR).

Introduction

Hydraulic fracturing is one of the main approaches to increase the production and injection in the process of oilfield production and development. Precise knowledge of the fracture's parameters, such as location, orientation and size, is of great significance to optimize fracturing process, guide development well pattern deployment and manage the reservoir performance. Tiltmeter monitoring method is an emerging fracture monitoring technique, which is characterized by such characters as safety, environment protection, convenience of maintenance and accurate monitoring results. It has very high accuracy in determining the fracture's dip angle and orientation.

The SA method, which doesn't need any prior fracture information and has a significantly larger convergent region, is a better option for tiltmeter-based hydraulic fracture monitoring compared with the traditional ones. According the tilt measurements, the new approach can inverse the fracture's key parameters such as the central position, orientation, dip and dimensions accurately. However, while being utilized in a real monitoring process, its feasibility should be explored.

Theory and/or Method

Forward model

The forward model adopted here is based upon the dislocation model by Okada, which is shown in Figure 1. In Okada model, the hydraulic fracture is approximated into a rectangular dislocation model, and the tilt fields of both surface and downwhole due to a finite rectangular source are derived (Okada, 1992).

Inversion method

The inversion is based on the simulated annealing method, which is put forward by Kirkpatrick, etc., is a kind of heuristic random search algorithm based on the Monte Carlo method. The algorithm arises from the physical process for molten liquid's cooling and crystallization: when the liquid cooling rate slows to a certain level, the material will reach a stable equilibrium state, which is the lowest energy state. On the contrary, if the cooling rate is too fast, the material will turn into the low-energy state, and can't be completely crystallized, and further ends up with a metastable state. Based on the former physical process, in the application of simulated annealing algorithm, each model parameter to be inversion is treated as a molecule, and the objective function is taken as energy function, a simulation of the slowly decreasing temperature is used to control parameters for iterative inversion, making the objective function to the global minimum point.

In the inversion process, we define the summed relative error as the objective function, which can be expressed as formula (1), where N is the total number of observation stations, T_i^{cal} is the calculated tilt, Tiobs is the observed tilt, and ω_i is weighting coefficient which depends on the data quality of the ith observation.

$$\varphi = \frac{\sum_{i=1}^{N} \omega_i \left\| T_i^{cal} - T_i^{obs} \right\|}{\sum_{i=1}^{N} \omega_i \left\| T_i^{obs} \right\|} \qquad (1)$$

Synthetic Tests

The synthetic tests are composed into two parts: deployment configuration exploration and uncertainty analysis.

Deployment configuration exploration

In configuration exploration, the tiltmeters are arranged in circle with different radius around different fracture's central position. Under each radius, different number of tiltmeters is evenly deployed. For synthetic fracturing models with different inclination, the SA method is applied to inverse fracture parameters (dip, azimuth). Statistical analysis of the inversed results is conducted to explore appropriate deployment configuration of the observing system.

The configuration exploration is divided in two sections: synthetic tests for horizontal fracture and the vertical ones. As for horizontal fracture, radius is taken as a main variation, the tiltmeters are arranged in circles with the central part of the fracture as the center of the circle, taking different radius from the 5% to 90% of the depth of the well respectively. Under each radius, different number of tiltmeters is evenly deployed. Compared the inversed results with the real data, along with the statistical analysis, we obtain that while the tiltmeters are arranged in a radius which is smaller than 15% of the depth of the well, the SA method based inversion calculation fails to provide an accurate illustration for the fracture parameters owing to the fact that the irregular result which is supposed to converge to the measurement of 0 degree or 180 degree. In the range from 15% to 75% of the depth of the well, the inversed result shows an obvious convergence to 0° and 180° . When the number of the tiltmeters reaches a certain number (6 in this case), the inversed parameters' accuracy will not vary with the increase of the amount of the tiltmetres. As the length of the radius exceeds 75 % of the well's depth, the results dispersed and showed low accuracy.

Synthetic tests for vertical fracture based on the outgrowth of the horizontal ones, during this process, we make the tiltmeters' number as 6 and still, take the radius as a main variation, the radius ranging from 15% to 75% of the depth of the well, this time, under different radius, we set varied azimuth (stands for the angle between the fracture and the tiltmeters) as another variation to see its impact on the inversed results. However, the results show that only slightly influence is exerting by it, which means the azimuth influence is not a necessary consideration.

Uncertainty analysis

In uncertainty analysis, a group of Gaussian noise vector with random orientation in different noise level is superimposed to the synthetic tilt data at each surface site. For each noise level, the SA approach is applied to inverse the fracture's azimuth and dip for one hundred times and then conduct statistical analysis of the resulting mean and standard deviation to explore the applicable range of SNR. We take the noise level as the only variation here, which increase from10 nano-radian to110 nano-radian, which is equal to the signal level. To rule out the influence caused by the model itself, synthetic tilt data with no introduced is used as a comparison set.

Examples

Take the model parameters as follow to be an example: Depth in 1000m, height in 125m, length in 270m and width is0.0018m. For horizontal fracture, Figure 2 and Figure 3 respectively shows the statistical analysis under the radius of and 5% and15% well depth, the ordinate value stands for the number of occurrences among the total of 50 times' inversion, the abscissa values represents the dip. As an example, in figure 4, we have the statistical analysis under the radius of 80% well depth, in which situation, no apparent convergence is demonstrated.

The real dip for of the fracture for uncertainty analysis is 60° , and the azimuth is45° (Figure 5). The arrangement of six tiltmeters is set around the central position of the fracture with a radius of 45 % of the well depth (Figure 6). No noise is introduced in synthetic tilt data in the set whose result is shown in figure7, the average value for dip and azimuth is 45.21 and 59.95, along with a respective standard deviation of 0.18 and 0.35. (Figure 8) represent the statistical analysis while noise level is around 40 nano-radian, the average value for dips and azimuth is 46.33 and 46.33, along with a respective standard deviation of3.55and 8.50. As the noise level increases, when it is higher than 50 nano-radian (45.46% of the signal level) the standard deviation of dip and azimuth is 23.45 and 15.46, indicating the dispersion of the inversed parameters, which stands for huge difference between the real parameter and the inversed ones. (Figure 9) shows an example for this situation.

Conclusions

In this paper, we adopted a new method to inverse facture parameters through ground deformation obtained by tiltmeters and proposed an appropriate deployment configuration of the tiltmeter while fracture detection, including the number, range, and factor impact the inversion. Also, a SNR range for SA method based tiltmeter fracture detection was calculated. The results show that the SA method has a larger conversion region compared with conventional method, and be rid of the initial information of fracture in the first place which is required by other inverse theory. Simulation results shows that in the setting radius range from 15% to 75% of the depth of the well, titlmeter could effectively provide deformation data and when noise level is higher than certain degree this method will lose its precise. The appropriate deployment configuration can help us avoid setting unnecessary sites to reduce the overall cost and obtain higher accurate inversed fracture parameters to optimize the reservoir performance. Moreover, the applicable range of SNR can help us preclude situations in which the SA method can't be applied and further save time and cost for the whole procedure.

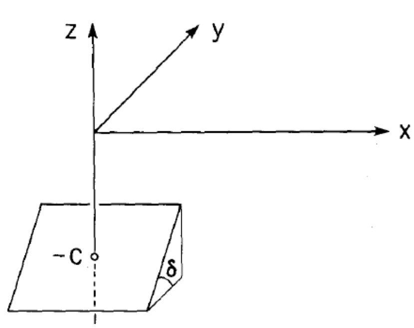

Figure.1

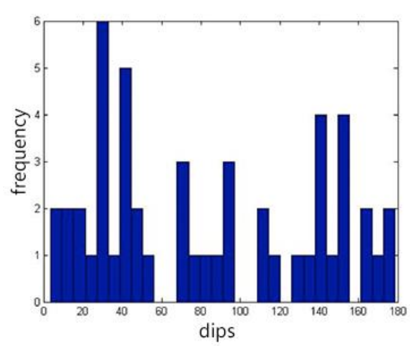

Figure.2

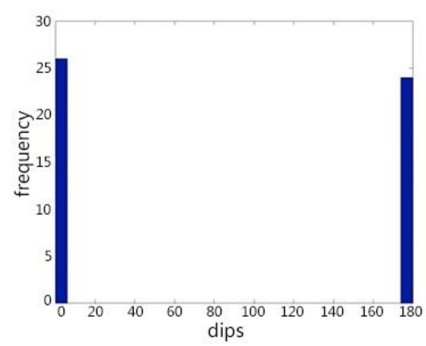

Figure.3

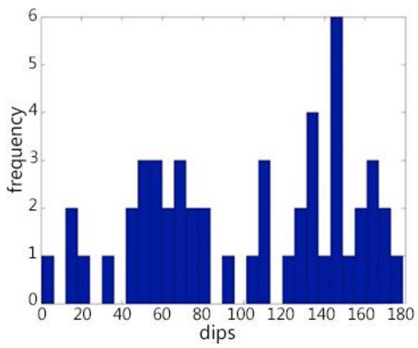

Figure.4

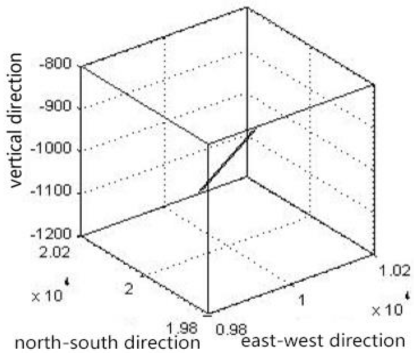

Figure.5

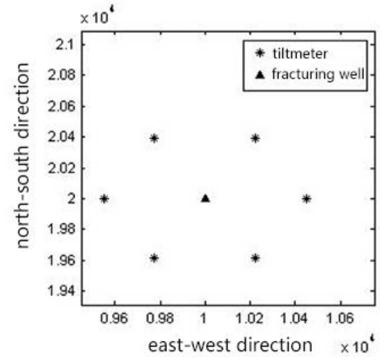

Figure.6

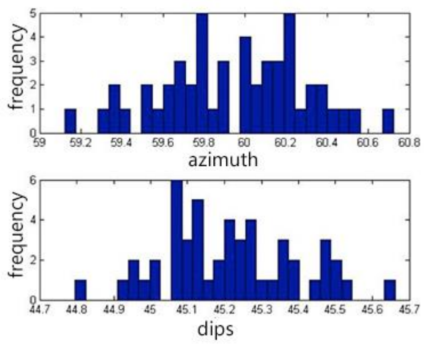

Figure.7

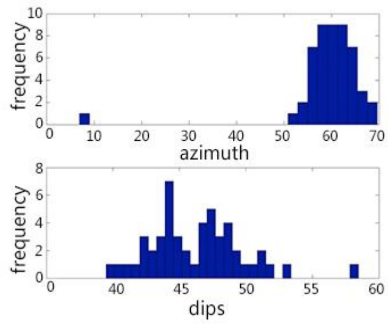

Figure.8

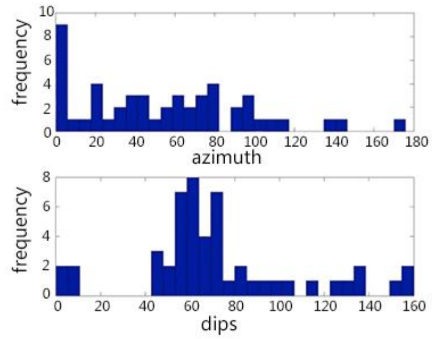

Figure.9

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