Inversion method of horizontal well boundary detection based on geo-steering electromagnetic wave measuring instrument

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Abstract. Based on the adaptive damping Gauss-Newton Inversion Algorithm, this paper studies the inversion method of the horizontal well boundary detection by the geo-potential electromagnetic wave measuring instrument. Based on the drilling trajectory and logging data of a real horizontal well, the simulation inversion is used to detect the position of formation boundary, and the validity of the inversion method is verified.

1. Introduction
Geo-steering logging inversion is the acquisition of the formation characteristic parameters and well trajectory parameters obtained from logging data. Many papers have been published on inversion of formation conductivity parameters at home and abroad. The development of electromagnetic wave measuring instrument for geo-steering while drilling in China is relatively late. And the corresponding interpretation and processing methods of logging data are also in the initial stage. Based on adaptive damping Gauss-Newton Inversion Algorithm, this paper studies how to extract formation boundary information from horizontal well logging data. The validity of the inversion algorithm is verified by the edge detection inversion of a real oilfield logging data.

2. Gauss-Newton inversion method for electrical logging problems
The inversion problem of formation boundary detection with geo-steering electromagnetic logging can be described as

\[ d = F(x; H, \sigma_{sh1}, \sigma_{sh2}, \sigma_j) \]  

In the formula, \( d \) is the directional logging response (Directional amplitude \( Att \) or directional phase shift \( PS \)), \( x = [x_1, x_2, x_3, \cdots, x_M] \) is the distance between the instrument and the formation boundary, \( H \) is the target layer thickness, \( \sigma_{sh1} \) is the upper adjacent rock conductivity, \( \sigma_{sh2} \) is the lower adjacent rock conductivity, \( \sigma_j \) is the reservoir conductivity.

In this paper, adaptive damping Gauss-Newton method is used to invert the boundary of horizontal well. Finding the optimal solution of objective function based on least square principle is the core idea of Gauss-Newton method. The Algorithm does not need to compute the quadratic partial derivative matrix. The speed of inversion calculation is improved and its convergence rate is comparable to that of Newton approximation.

The actual inversion is not to solve the equations as shown in Formula (1), but to find the minimum error square sum of the parameters of the model to be inversion, that is...
The optimal solution is defined as \( x = [x_1, x_2, x_3, \ldots, x_M] \).

\( \varepsilon(x) \) is defined the error between the forward calculated response \( S(x) \) and the log data \( d \)

\[ \varepsilon(x) = S(x) - d \]  

The objective function is defined as

\[ O(x) = \frac{1}{2} \left[ \| \varepsilon(x) \| ^2 + \lambda \| x - x_p \| ^2 \right] \]  

Where \( x_p \) is the initial value and \( \lambda \) is the regularization factor.

Expand the Taylor series of the objective function at the nth iteration and intercept the first three terms

\[ O(x_n + p_n) \approx O(x_n) + g^T(x_n) \cdot p_n + \frac{1}{2} p_n^T \cdot \nabla^2 O(x_n) \cdot p_n \]  

In the formula, \( p_n = x_{n+1} - x_n \), \( g(x) \) is the gradient of the objective function, obtained from formula (4)

\[ g(x) = \nabla O(x) = \nabla^{-1}(x) \cdot \varepsilon(x) + \lambda (x - x_p) \]  

here, \( J(x) \) is a Jacobi Matrix.

3. Inverse problem of horizontal well boundary detection with geosteering survey instrument

Based on the axial coil system of conventional logging-while-drilling tool, the geo-steering electromagnetic wave measuring instrument adds the inclined coil system to be used for geo-steering. In order to determine the distance between the front of the drill bit and the formation boundary more accurately and conduct the geological guidance better, it is necessary to invert the distance between the instrument and the formation boundary.

This section based on a real horizontal well drilling trajectory and logging data, simulation inversion detection formation boundary location, verify the effectiveness of the inversion method.

The amplitude of the Directional response of the formation model is \( Att_n \), the amplitude of the actual log response is \( Att_m \), the directional phase shift of the formation model is \( PS_n \), and the directional response phase shift of the actual log response is \( PS_m \).

So, the error between the forward calculated response \( S(x) \), and the log data \( M \), can be defined as

\[ \varepsilon_1 = \sum_{j=1}^{J} \left( Att_n^j - Att_m^j \right)^2 \]  

\[ \varepsilon_2 = \sum_{j=1}^{J} \left( PS_n^j - PS_m^j \right)^2 \]  

Then the objective function is

\[ \varepsilon = \varepsilon_1 + \varepsilon_2 = \sum_{j=1}^{J} \left( Att_n^j - Att_m^j \right)^2 + \sum_{j=1}^{J} \left( PS_n^j - PS_m^j \right)^2 \]  

\( J \) is the number of directional measurement coil arrays. The following constraints need to be met:

(1) The target layer in the database is twice as thick as the directional detection distance at the corresponding frequency to ensure the inversion of the stratigraphic boundary.

(2) The ATT and PS values are higher than the minimum (sensitivity or threshold) that the actual value can be measured by the instrument. In this paper, the minimum amplitude sensitivity is set to
0.03dB, the phase shift caused by the formation can be distinguished should exceed 0.5°, and the phase ranges from $-\pi$ to $\pi$.

4. Inverse problem of horizontal well boundary detection with geosteering survey instruments

Based on a real horizontal well drilling trajectory and logging data, we will simulate the inversion to detect the formation boundary position, and verify the validity of the inversion method.

An actual horizontal well is shown in Fig. 1. Well Xu 18 and well Zhao Ping 6 are adjacent straight holes. As can be seen from Fig. 2-6, a horizontal well drilling through three oil and gas reservoirs encounters a fault, passes through the fault and enters the lower wall rock formation, drilling to a depth of 2796 meters in the Lower Wall rock formation and re-entering the target formation.

From figure 1, it can be seen that the drilling trajectory and the formation structure around the wellbore are very complex. However, analysis shows that each horizontal well can be approximately modeled as a three-layer model. In inversion, the stratigraphic model is simplified to three strata, namely, the upper and lower surrounding rock strata and the target strata. If the target layer is thick and the instrument is near the boundary, the model can be further simplified to two layers.

Since the characteristics of horizontal interval are mainly horizontal extension and inclined extension, these two characteristics are also taken into account in the inversion, as shown in Figure 2.

4.1. Thin layer model

A three-layer formation model is established, and the trajectory of the geopotential electromagnetic wave measuring instrument in the formation is shown in Fig. 3. The position of the tool in horizontal drilling is the horizontal axis and the vertical axis is the vertical depth of the formation. The layer between the blue and red lines is 2 meters thick. The interface between the upper wall rock and the target layer is 2.5 meters above the vertical coordinates, and the interface between the lower wall rock and the target layer is 0.5 meters above the vertical coordinates.

For the eight points shown in figure 3, the eight points are respectively located at the monotone descending interval in the target layer, the step with descending trend at the minimum point in the target layer, the maximum point of the trajectory in the target layer, and the minimum point of the instrument trajectory in the surrounding rock layer, the step with ascending trend, the surrounding rock layer with maximum value, and the monotone ascending interval in the target layer. When the source distance is 84inch, the inversion results of eight typical positions is shown in Table 1.
The target layer
The upper surrounding rock layer
Figure 3. Instrumental trajectory in 2-meter-thick formation

| Parameters                        | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Point 6 | Point 7 | Point 8 |
|-----------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|
| Theoretical values (m)            | 2.1     | 1.5     | 1.4     | 1.0     | 0.2     | 1.3     | 2.7     | 1.8     |
| Response values (dB)              | 2.08293 | 0.00053 | -0.25806 | -1.7735 | -3.696031 | -0.5349 | 3.6686 | 0.88821 |
| Initial value (m)                 | 0.2     | 0.7     | 0.7     | 1.2     | -0.1    | 0.9     | -0.1    | 0.5     |
| The distance from the upper boundary (m) | 0.3971 | 1.0035 | 1.0954 | 1.4962 | 1.2034 | -0.1997 | 0.7039 |
| The distance from the lower boundary (m) | 1.6039 | 0.9974 | 0.8962 | 0.4979 | -0.2993 | 0.8037 | 1.2961 |
| Absolute error 1 (m)              | -0.0029 | 0.0035 | -0.0046 | -0.0038 | -0.0007 | 0.0034 | 0.0007 |
| Absolute error 2 (m)              | 0.0039 | -0.0026 | -0.0038 | -0.0021 | 0.00069 | 0.0037 | -0.0039 |
| Relative error 1                  | -0.725% | 0.35%  | -0.418% | -0.253% | 0.2833% | -0.17%  | 0.5571% |
| Relative error 2                  | 0.2438% | -0.26% | -0.422% | -0.42%  | 0.23%   | 0.4625% | -0.3%  |

The parameters in the table are described as follows:

1. Theoretical values: The vertical position of the instrument in the formation for forward calculation;
2. Response values: The directional amplitudes obtained by forward calculation based on the given parameters of the formation model;
3. Initial value: The initial value of the given search range after the analysis of the directional amplitude response;
4. The distance from the upper boundary: the distance Inversion value between instrument and upper boundary;
5. The distance from the lower boundary: the distance Inversion value between instrument and lower boundary;
6. Absolute error 1: The difference between the actual inversion value and the upper boundary minus the theoretical value;
7. Absolute error 2: Relative error 2: The difference between the actual inversion value and the lower boundary minus the theoretical value.
(8) Relative error 1: The absolute error 1 over the theoretical value; (9) Relative error 2: The absolute error 1 over the theoretical value.

4.2. Thick layer model

![Diagram of instrumental trajectory in 4-meter-thick formation]

Figure 4. Instrumental trajectory in 4-meter-thick formation

The trajectory of the geopotential electromagnetic wave measuring instrument in the formation is shown in Fig. 4. The position of the tool in horizontal drilling is the horizontal axis and the vertical axis is the vertical depth of the formation. The layer between the blue and red lines is 4 meters thick. The interface between the upper wall rock and the target layer is 5 meters above the vertical coordinates, and the interface between the lower wall rock and the target layer is 1 meter above the vertical coordinates.

When the source distance is 84 inch, the inversion results of eight typical positions is shown in Table 2.

Because the target layer thickness is known, we only need to invert the distance of the instrument from one stratigraphic boundary to know the distance of the instrument from another stratigraphic boundary. In this paper, the inversion value is the distance between the Upper Wall Rock and the boundary of the target layer. A positive value indicates that the instrument is currently moving in the target layer, and a negative value indicates that the instrument is running in the upper surrounding rock.

| Parameters point | point 1 | point 2 | point 3 | point 4 | point 5 | point 6 | point 7 | point 8 | point 9 |
|------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Theoretical values (m) | 1.4     | 0.9     | 0.2     | 1.0     | 2.4     | 1.4     | 1.6     | 2.7     | 1.1     |
| Response values (dB) | -2.7125 | -5.2161 | -1.594  | -5.3498 | -0.5258 | -2.7125 | -1.9498 | -0.6726 | -4.5432 |
| Initial value (m) | 0.2     | -0.1    | -0.7    | 0.1     | 2.0     | 2.8     | 3.1     | 2.0     | 0.1     |
| The distance from the rupper boundary (m) | 3.6035 | 2.5973  | 3.6049  | 3.3966  | 2.3032  |
| The distance from the lower boundary (m) | 0.4035 | -0.10032 | -0.8036 | 0.0039  | 1.3977  | 0.40084 | 0.5974  | 1.3032  | 0.09971 |
| Absolute error 1 (m) | 0.0035  | -0.0027 | 0.0049  | -0.0034 | 0.0032  |
| Absolute error 2 (m) | 0.0035  | 0.00032 | -0.0036 | 0.0039  | -0.0023 | 0.00084 | -0.0026 | 0.0032  | 0.00029 |
| Relative error 1 | 0.0972% | -0.104% | 0.1361% | -0.164% | 0.21%   | -0.433% | 0.2462% | -0.29%  |
| Relative error 2 | 0.875%  | -0.32%  | 0.45%   | -0.164% | 0.21%   | -0.433% | 0.2462% | -0.29%  |
5. CONCLUSION
The application of adaptive damping gauss Newton Inversion Algorithm in directional electromagnetic wave measuring instrument for horizontal well boundary detection is studied in detail. Based on the drilling trajectory and logging data of a horizontal well, the simulation inversion method is used to detect the position of formation boundary, and the validity of the inversion method is verified.

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