The study of imaging method for the moving controlled-source electromagnetic method

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Received: 19 November 2018 / Accepted: 4 September 2019 / Published online: 9 September 2019
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Abstract

Improving the accuracy and enhancing the reliability of controlled-source electromagnetic (CSEM) inversion in oil exploration in order to identify the interface between oil and water is a great challenge. In this paper, we proposed a variable-angle geometry imaging method by moving the source of CSEM (MCSEM). Firstly, based on the concept of multi-channel transient electromagnetic method, we obtained the quantitative relationship between the offset and detection depth, and then the geometry imaging principle of MCSEM was set up. Secondly, the feasibility study of the geometry imaging method was tested through the 1-D and 3-D forward modeling. Finally, by analyzing the collected field data of MCSEM method in Daqing oil reservoir, high-accuracy pseudo-apparent resistivity profile was obtained based on the geometry imaging method with the help of well-logging calibration. The results showed good compatibility with the 2-D TEM resistivity inversion which demonstrates that the MCSEM has great prospect potential in the identification of oil–water interface explorations.

Keywords Imaging method · Moving controlled source · Apparent resistivity · Two-dimensional inversion

Introduction

With the continuous production and exploration of oil field, the large resistivity difference between the oil-bearing reservoir and the surrounding water formation provides a good geophysical foundation for the application of electromagnetic method in the continuous monitoring of residual oil and the identification of oil–water interface. In recent years, various controlled-source electromagnetic exploration technologies have been used in oil and gas exploration. Among these methods, the transient (time-domain) electromagnetic (TEM) method is widely used in exploration geophysics in both petroleum and mineral applications for its many advantages such as high data acquisition quality, small field source impact, deeper exploration depths and its strong ability to solve geological problems (Zhdanov and Keller 1994). Thus,

TEM is considered to be one of the most promising electromagnetic exploration methods.

Hence, Liu and Deng (1993) successfully carried out LOTEM deep structure detection test research in Tangshan area of China. Based on the achieved initial results, the method was introduced into oil and gas exploration. In the late 1990s, the LOTEM method was carried out on oil and gas exploration test for the first time in southern China (Yan et al. 1999, 2001). They also successfully obtained high-quality LOTEM data and satisfactory inversion results which proved to be consistent with geological formations. At the same time, other geophysicists conducted numerous studies on data processing, forward modeling and inversion methods. For example, Bai et al. (2003) proposed the definition of the TEM resistivity algorithm for the all-time apparent resistivity. Hoheisel et al. (2004) provided the basis for the inversion of LOTEM by conducting a 1-D forward modeling while taking into consideration the effects of induced polarization. The interpretation of this method was based on a simple 1-D inversion of the data at any given observation point. However, relatively large separation distances between the observation points proved challenging during the TEM surveys. Hence, a new modification of this technique was proposed, called multi-transient electromagnetic (MTEM) method (Hobbs et al. 2005). The traditional

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imaging method of MTEM is similar to the seismic method, with the angle of receiving and transmitting point explored underground being 45° from the surface, and the intersection point is taken as the real position of calculated apparent resistivity value (Hobbs and Linfoot 2007). In recent years, Ziolkowski et al. (2007, 2010, 2011) predicted natural gas reservoirs using the multi-channel transient electromagnetic detection system, but the rigorous 2-D and 3-D inversion of the MTEM data was a very challenging problem because of the enormous computations required for forward modeling of the multi-transmitter and multi-receiver MTEM data.

Therefore, in this paper we proposed a variable-angle geometry imaging method for the moving controlled-source electromagnetic (MCSEM) method. This imaging method is based on the theory of TEM and MTEM method and uses electric dipole as source to carry out a series of analyses on the forward modeling and application. According to the logging resistivity data from the study area, 1-D and 3-D forward models were established to verify the feasibility of this method. Finally, the field test was conducted in Daqing Oil Field of China, whereby the electric field response was recorded at the earth surface. After data processing, the apparent resistivity of the geometry imaging profile of MCSEM method was obtained and its results were compared to the ones obtained with 2-D TEM resistivity inversion.

Methodology

The apparent resistivity and detection depth formula of MCSEM method

It is important to study the transient electric field response of horizontal electric dipole source in uniform half-space when analyzing and discussing the characteristics and variation law of electric field response of complex geoelectric profile models. According to the theory of TEM, the time-domain electric field function $E(\rho, r, t)$ under the excitation condition of the pulse source for the uniform half-space can be obtained following (Kaufman and Keller 1987) as:

$$E(\rho, r, t) = \frac{\rho}{8\pi\sqrt{\pi}c^3} \exp\left(\frac{-r^2}{c^2 4t}\right) t^{-\frac{5}{2}} \quad (1)$$

where ρ is the resistivity (Ω m), r is the offset (m), t is the time (s) and c^2 is the ratio of the resistivity to permeability given as $c^2 = \rho/\mu$.

By calculating the time derivative of electric field response function, we can obtain the mathematical equation of the electric field which responds to the rate of change. According to this equation, we can derive the relationship between the amplitude of the electric field component and

time. Hence, the apparent resistivity formula when the electric field amplitude is at maximum can be obtained as well as the peak time. Finally, the apparent resistivity calculation formula for the imaging method of MCSEM method can be given as follows (Ziolkowski et al. 2007):

$$\rho_a(t_{\text{peak}}) = \frac{u_0 r^2}{10 t_{\text{peak}}} \quad (2)$$

where ρ_a is the apparent resistivity (Ω m), r is the offsite (m), t_{peak} is the time when the electric field amplitude is at maximum (s) and u_0 is the permeability in vacuum (H/m).

Based on the theory of electromagnetic diffusion, we obtained a transformation curve such that it can be converted to a resistivity versus depth curve when the electromagnetic wave propagates through the medium. Furthermore, the curve was used to calculate the diffusion velocity. In uniform half-space, the diffusion velocity was obtained using the formula given by Yan et al. (2002) as follows:

$$v_d(t_{\text{peak}}) = k \sqrt{\frac{\rho_a}{u_0 \cdot t_{\text{peak}}}} \quad (3)$$

where v_d is the diffusion velocity (m/s), k is a constant, ρ_a is the apparent resistivity (Ω m), t_{peak} is the time when the electric field amplitude is at maximum (s) and u_0 is the permeability in vacuum (H/m).

Then, the formula of diffusion depth was obtained by:

$$D(t_{\text{peak}}) = v_d \cdot t_{\text{peak}} = k \sqrt{\frac{\rho_a \cdot t_{\text{peak}}}{u_0}} \quad (4)$$

Combining Eqs. (2) and (4), the diffusion depth can be abbreviated as:

$$D(t_{\text{peak}}) = k \frac{r}{\sqrt{10}} \quad (5)$$

Thus, constant k can be calculated by the diffusion depth and offset.

MCSEM method geometry imaging principle

The MCSEM method is based on the theory of magnetotelluric diffusion. We used the electric dipole source to transmit step current into the ground, and the receiver station array was arranged on the measuring line to receive the underground electric field signals. The derivative curves of electric field versus time were obtained based on the observed electric field data which were processed by the Yangtze University transient electromagnetic (YUTEM) processing software. Following that, the apparent resistivity of imaging MCSEM was obtained according to Eq. (2). The calculated

apparent resistivity is located at a downward crossing point between the source and the receiving station at an angle of α , which could be obtained by the offset and diffusion depth. The diffusion depth was calibrated using well-logging data. We also kept the source and observation point stationary and then moved them simultaneously. Thereafter, the apparent resistivity profile of the underground geological structure was obtained. The field observation mode and geometry imaging method of MCSEM are shown in Fig. 1.

Feasibility study

Geological characteristics of the study area

To study the feasibility of the MCSEM geometry imaging method, the field test was carried out in Daqing Oil Field located in Daqing City, Heilongjiang Province. Geographically, it is located in the middle of the Sancha sag which is in the center of the northern Songliao Basin and it intersects with Songfangtuan, Shengping and Xujiaweizi Oil Fields. The sedimentary stratum of the Songliao Basin includes the Carboniferous–Permian, Jurassic, Lower Cretaceous, Cretaceous, Tertiary and Quaternary. It is one of the most complete areas of the Chinese continental cretaceous system, and the sediment thickness is close to 10 km. In the basin, the Cretaceous has a two-layer structure of lower fault and upper sag (Gao et al. 2002). In the upper part of the area, there is a depression basin with third of its section consisting of the Quantou Formation, the Qingshankou Formation, the Yaojia Formation, the Nenjiang Formation and the Sifangtai Formation. All of these formations are the main targets for oil exploration. The lower part is a faulted basin, which was

formed by the Volcanic Ridge Formation, Shahezi Formation, Yingcheng Formation, Dengyucu Formation and Quantou Formation. These formations are dominated by natural gas exploration (Guo 2017). With the exploration and development of Daqing Oil Field in recent years, the high-precision 3-D seismic exploration (Huang 2010), tight oil explorations and development studies have been carried out in the early stages of exploration as well as evaluation (Lu et al. 2017). However, with the development of oil fields in the middle and late stages of the exploration, separating the oil–water interface has become a huge challenge.

TEM 1-D forward modeling

In order to verify the feasibility of TEM method in the study area, six characteristic electric logging curves were collected as shown in Fig. 2. The results show that the reservoir resistivity is about 5–10 Ω m and the surrounding rock resistivity is 2–3 Ω m. Also, the reservoir thickness was observed to be around 40 m and the top buried depth was around 1480 m.

A 1-D TEM forward modeling was performed according to the geoelectric model established by the logging curve in the test area (Daqing Oil Field), and the results are shown in Fig. 3. This forward modeling mainly examined the influence of reservoir thickness variation from 0 m to 40 m on apparent resistivity. The results showed that the forward curve anomaly was recognizable and theoretically distinguishable which provided the basis for the 3-D forward modeling of the MCSEM method.

Fig. 1 Field observation model and the MCSEM geometry imaging method

Fig. 2 Logging curve in Daqing Oil Field

MCSEM geometry imaging method feasibility study

According to the geological structure of Songliao Basin and the electric logging curve of the study area, a 3-D forward model for the MCSEM geometry imaging method was

established as shown in Fig. 4. We set the length, width and height of the abnormal body to be 1 km, 1 km and 0.2 km, respectively, in this 3-D forward modeling. Its depth was set to 1.4 km, and the resistivities of the abnormal body and the surrounding rock were $10\Omega\text{ m}$ and $2\Omega\text{ m}$, respectively.

As shown in Fig. 5, the transmitting source and receiver array for the MCSEM geometry imaging profile were laid along the X-axis. The length of the electric dipole source was 1.2 km with a spacing of about 100 m. There were five transmitting sources and arrays used to obtain the electric field response.

Using the principle of TEM method to calculate the electric field value E_x of the surface in combination with the MCSEM method, a 3-D forward geometry imaging result was obtained as shown in Fig. 6. The 3-D forward result showed that the abnormal body resistivity in this imaging method was about $7\Omega\text{ m}$. This observed result was higher than the surrounding rock resistivity of $3\Omega\text{ m}$, and the simulation result anomaly could be clearly identified and distinguished, which proved that the MCSEM method was feasible.

MCSEM geometry imaging method field test results

Field test equipment

During the MCSEM field test, we used the T200 transmitter device with a total of five electric dipole sources with source spacing of about 100 m. The receiving device was V8 together with its supporting device accessories. The number of electric fields receiving channels was between 12 and 13, and the dot pitch was 100 m. The equipment schematic of the transmitter source and receiver array is shown in Fig. 7.

Fig. 3 TEM 1-D forward results (left: 1-D model, right: the apparent resistivity results with the thickness variation of oil-bearing layer)

Fig. 4 Three-dimensional model set up in reference to the logging data

Field test data processing

The MCSEM method collected the time-domain electromagnetic signal and recorded the electric field attenuation signal from 4 to 8 s after the transmission source signal was turned off. The received signal was imported into the

YUTEM processing software, and the data superposition processing was performed to directly derive the secondary field electromagnetic field signal. The YUTEM software enabled us to check the pre-stack processing of the original electromagnetic data curve in real time for the electric field E_x and of the dipole source. The data processing results showed that the quality of the data was good and the consistency was high. The secondary electric field signals of multi-source observations were obtained through data postprocessing, which provided reliable basic data for the geological interpretation.

After processing the field data, the poststack processing curves of the electric field value over time were obtained. There were five transmitter sources and five receiver arrays which were used to collect the field data in this paper, and every receiver array produced one graph as shown in Fig. 8.

MCSEM geometry imaging results

Through postprocessing of the data, the electric field response at each receiving point from each transmitting

Fig. 5 MCSEM apparent resistivity geometry imaging profile

Fig. 6 Three-dimensional model testing for the apparent resistivity geometry imaging

Fig. 7 Layout for MCSEM with V8 multi-functional electromagnetic exploration system

Fig. 8 Impulse response of electric field for the five transmitter sources. **a** The dipole source is S0 and the receiver array from R1 to R10; **b** The dipole source is S1 and the receiver array from R2

to R12; **c** The dipole source is S2 and the receiver array from R3 to R12; **d** The dipole source is S3 and the receiver array from R4 to R14; **e** The dipole source is S4 and the receiver array from R5 to R14

source was obtained. Using the numerical calculation method to get the peak time corresponding to the response curve of each measuring point, the apparent resistivity was obtained by using Eq. (2). Figure 9 shows the geometry

imaged apparent resistivity distribution (in color) and the 2-D TEM inverted resistivity profile (the contours). According to the pre-information of geology and well-logging curves of the study area, the resistivity of reservoir target

Fig. 9 Geometry imaged apparent resistivity profile (in color) of MCSEM compared with the result of 2-D TEM inversion (the contour)

layer is higher than the surrounding rock and the depth is between 1400 and 1600 m. The 2-D TEM inversion result shows three high-resistivity anomalies (red dotted circles: A1, A2 and A3) in the reservoir target layer which could be considered as residual oil reservoir. There are also two resistivity anomalies (colored contours in the black frame) in the geometry imaged apparent resistivity distribution area which correspond to A2 anomaly inverted by 2-D TEM. The consistence shows that the MCSEM geometry imaging method has great prospect potential in the identification of oil–water interface exploration.

Conclusion

In this paper, we have proposed a variable-angle geometry imaging method for the MCSEM in order to improve the accuracy and enhance the reliability of the CSEM method in oil exploration. Based on the theory of magnetotelluric diffusion and MTEM method, the principle of MCSEM method geometry imaging was obtained. The imaging angle was determined by offset and diffusion depth, and the latter was mainly according to the logging data. Through a series of analyses on the study area, the 3-D forward model was set up and the geometry imaging method of MCSEM was carried out based on the electrical components forwarded by the 3-D model. The results showed that the 3-D anomaly can be clearly imaged using MCSEM method. Finally, the MCSEM method was applied to the field-observed data collected from Daqing Oil Field reservoir. The apparent resistivity of the target layer was then imaged with the help of well-logging data from the field area. Comparing with the results obtained from 2-D TEM resistivity inversion, the results of MCSEM geometry imaging method were consistent with the geological structure and the electric logging curve of the study area, which proved that the geometry imaging method can be used in residual oil and gas exploration. Unlike the conventional

inversion methods, the MCSEM geometry imaging method features good stability, validity and uniqueness.

Acknowledgements We gratefully acknowledge the Science Research and Technology Development Project of China National Petroleum Corporation (2017D-5006-16), the National Natural Science Foundation of China (41774082) and the National Key R&D Program of China (2017YFC0601804). The funders had no conflict of interest or any role in the study design, data collection, and analysis, decision to publish or preparation of the manuscript.

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