The effect factors analysis of the cave formation based on the LWD resistivity imaging method

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Abstract. The cave formation has strong non-homogeneity and the well logging response mechanism of it is very complex, which is of great significance to be studied. Based on the 3D finite element method, the logging response of the Logging While Drilling (LWD) resistivity imaging tool is simulated. The effects of cave diameter, cave extension and resistivity contrast between cave formation and background formation on ratio of measurement signals are investigated using a single cave model. The results show that the existence of the borehole has a great influence on the measurement signal, so it needs to be corrected or the measurement electrode of the tool should be close to the borehole. When the diameter of the cave is larger than a certain value, the relationship between the cave extension and the measurement signal can be quantitatively described. However, the resistivity contrast between the cave formation and the background formation shows a power index relationship under different cave diameter. The simulation results can provide a theoretical basis for the identification and interpretation of LWD resistivity imaging tool.

1. Introduction
In the field of petroleum exploration, resistivity imaging logging is a technology that directly measures the images of geological structures of the borehole. It can visually reflect the structure near the borehole, such as fracture, cave, etc. With the development of technology, resistivity imaging logging tool is also successfully transitioning from wireline measurement to LWD measurement. Uploading the measurement data to the ground while drilling, real-time geological environment monitoring can be realized, which ensures safety drilling and realizes geosteering [1-3].

Carbonate and volcanic rock have strong non-homogeneity, and logging interpretation is difficult. For these kinds of reservoirs, the tool has better applications effect. Because the cave can not only be used as a storage space, but also as a kind of oil and gas connection channel. Interpretation people can discover the existence of the cave easily by using the resistivity images of the borehole. Based on the advantages of the above-mentioned LWD resistivity imaging technique, the tool is more and more used in cave and fracture formations [4-6]. But there are few research reports on the mechanism of the logging response in the cave formation, which hinders us using the logging data in the cave formation. So it is necessary to study the mechanism using numerical simulation.

In this paper, 3D FEM is used to systematically simulate the influence of cave diameter, cave extension and bedrock resistivity on the measurement signal. The results reveal the response law of LWD resistivity imaging tool to the caves, and provide a theoretical basis for the identification and evaluation of the caves.
2. Simulation results
Many people have done a lot of simulation work about the logging response in the cave formation, but most of them focus on the dual laterolog tool and electromagnetic wave propagation logging tool[7-11]. There are few reports about the logging response mechanism of the LWD resistivity imaging tool, so it is necessary to use numerical simulation method to study its mechanism.

The dual laterolog has a good identification and evaluation effect for the cave with a diameter of more than 1 m, while the LWD resistivity imaging method can show the cave images when the diameter of cave is less than 1 m. Therefore, this paper focuses on caves with a diameter of less than 1 m.

Cave formations are generally asymmetric, so they need to be simulated using 3D models. 3D FEM is used in this paper. Figure 1 shows a cross-section of the formation model of a single cave. The model consists of LWD resistivity imaging tool, borehole, background formation and cave. The button electrode is used to collect current, and it consists of four electrodes, named 1, 2, 3, 4. Each electrode is 90 degrees apart in circumferential direction. Electrode 1 is right towards the cave. The cave is vertical to the borehole.

![Figure 1. Schematic of single cave model](image)

When analyzing the influence of cave extension, cave resistivity and bedrock resistivity on the measurement signal, the cave is divided into two sizes: medium cave (0.01 m in diameter) and large cave (0.05 m in diameter). Table 1 are simulation parameters of single cave. The influences of cave diameter, cave extension and resistivity contrast on the measurement signal are investigated.

| Effect factor       | Diameter (m) | Extension (m) | Mud resistivity (Ω·m) | Cave resistivity (Ω·m) | Background formation resistivity (Ω·m) |
|---------------------|--------------|---------------|-----------------------|-----------------------|---------------------------------------|
| Diameter            | 0.002-0.1    | 0.5           | 1                     | 1                     | 100                                   |
| Extension           | 0.01 0.05    | 0.02-0.5      | 1                     | 1                     | 100                                   |
| Resistivity contrast| 0.01 0.05    | 0.5           | 0.2-20                | 0.2-20                | 100                                   |

2.1. Cave diameter
The shape of the cave is a cylinder in the 3D FEM model, which is orthogonal to the borehole and drilled through by it. The diameter of the cave is smaller than that of the borehole, so the intersection line is irregular. When the diameter difference between borehole and cave is large, the intersecting line is close to a circle. Geologically, pores with a diameter of more than 0.002 m are called caves. Among them: the diameter of 0.002 m-0.005 m is small hole, the diameter of 0.005 m-0.01 m is medium hole, and the diameter of more than 0.01 m is large hole. The diameter of the cave studied in this paper is between
0.01 m and 0.1 m. The influence of cave with different diameter on the measurement signal is different. In Figure 2, Imax is the current signal measured by button electrode when the button electrode center and cave center are in the same longitudinal position. Imin is the current signal when the button electrode is facing the background formation, which is almost unchanged.

The existence of the borehole is investigated first. It can be seen from Figure 2a that the borehole has a great influence on the button electrode 1 measurement signal when the borehole exists. When the cave diameter is less than 0.01 m (area A), the measurement signal is larger. The measurement signal becomes gradually smaller with the increase of the diameter, and the measurement signal almost comes from the borehole. Affected by the borehole, the button electrode 1 can not identify the cave; when the cave diameter is greater than 0.01 m (area B), the measurement signal increases to a stable level with the increase of the cave diameter. Figure 2b shows the relationship between the measurement signal and the cave diameter without the borehole. As the cave diameter changes from 0.002 m to 0.1 m, the measurement signal is gradually increasing with the increasing of the cave diameter. The relationship between the cave diameter and Imax/Imin is linear. Figure 2a and Figure 2b show that the measurement signal from other directions is not sensitive to the cave, and the value of Imax/Imin equals to 1. Therefore, effectively eliminating the influence of borehole is the key to accurately identify caves. The main method is to put the button electrodes near the well wall or correct the effect of the borehole.

2.2. Cave extension

Wireline microresistivity imaging tool can directly display the distribution characteristics of caves, but its depth of investigation (DOI) is limited just providing the cave information of the borehole wall. Therefore, it is difficult to detect the radial extension characteristics of caves. The DOI of dual laterolog is deeper than that of the above tool, but it is not sensitive to caves with diameter less than 1 m. Compared with the above two tools, the DOI of LWD resistivity imaging tool is deeper than that of wireline type tool. And it has a better recognition of caves with smaller diameter.

Figure 3a shows that the measured signals change with the increase of the extension in the medium cave. When the extension varies from 0.1 m to 0.5 m, the signals of electrodes 2, 3, 4 are almost unchanged, and the ratio of Imax and Imin is close to 1, indicating that the cave has little impact on the measured signals. When the cave extension is less than 0.15 m, the measured signal of button electrode 1 has a nonlinear relationship with the cave extension, and the Imax/Imin is far greater than 1. Considering the small diameter of the cave, the result is mainly caused by the borehole effect. When the cave extension is greater than 0.15 m, the current signal measured by the button electrode 1 does not change with the cave extension, which shows that the effect of the borehole on the measurement results tends to be stable.

Figure 3b shows the relationship between the extension of the large cave and the ratio of measurement signal. It can be seen that with the increase of cave extension, the measurement signal of
button electrode 1 shows a power exponential relationship. Using the formula $I_{\text{max}}/I_{\text{min}} = 15.24 \cdot E^{0.6}$ to fits the relationship between cave extension $E$ and $I_{\text{max}}/I_{\text{min}}$, table 2 compares the relative error between the simulation data and the calculated data by it. It can be seen that the error of most data is within 5% except for individual points, which indicates that the radial extension of the large cave can be obtained by applying the above formula. According to the theoretical calculation of different cave diameter, we can get the corresponding extension calculation formula of different cave diameters. A large number of simulations of the relationship between the cave extension and the measured signal with different diameters demonstrate the above conclusions, but it should be noted that the cave extension can only be calculated by this model when the diameter of the large cave is between 0.01 m and 0.05 m.

![Figure 3](image)

**Figure 3. The effect of cave extension on ratio of measurement signals**

| Extension (m) | $I_{\text{max}}/I_{\text{min}}$ (simulation data) | $I_{\text{max}}/I_{\text{min}}$ (fitting data) | Relative error (%) |
|--------------|-----------------------------------------------|-----------------------------------------------|-------------------|
| 0.02         | 1.59                                          | 1.46                                          | 8.36              |
| 0.04         | 2.23                                          | 2.21                                          | 0.63              |
| 0.06         | 2.64                                          | 2.82                                          | 6.95              |
| 0.08         | 3.24                                          | 3.35                                          | 3.38              |
| 0.10         | 3.71                                          | 3.83                                          | 3.30              |
| 0.15         | 4.75                                          | 4.89                                          | 2.90              |
| 0.20         | 5.7                                           | 5.81                                          | 1.39              |
| 0.25         | 6.59                                          | 6.64                                          | 0.76              |
| 0.30         | 7.40                                          | 7.41                                          | 0.07              |
| 0.35         | 8.21                                          | 8.12                                          | 1.09              |
| 0.40         | 9.00                                          | 8.80                                          | 2.25              |
| 0.45         | 9.66                                          | 9.45                                          | 2.18              |
| 0.50         | 10.41                                         | 10.06                                         | 3.39              |

2.3. Resistivity contrast of the cave formation and background formation
Tan et al. (2011) simulated the response of different fillers in the cave to dual laterolog. In the simulation, the resistivity of fillers ranged from 1 Ω·m to 500 Ω·m [12]. In this paper, it is assumed that the cave is filled with mud. And the resistivity of the fillers $R_m$ ranges from 0.2 Ω·m to 20 Ω·m, and the resistivity of background formation $R_b$ is fixed at 100 Ω·m. Figure 4 shows the logging response of button
electrode 1 to the direction of cave under the single cave model. Figure 4a and Figure 4b show the response characteristics of medium cave and large cave respectively. It can be seen that in the double logarithmic coordinate system, with the increase of \( \frac{R_m}{R_b} \), the current contrast measured by medium cave and large cave shows a linear decreasing trend (actually power index relationship), which is consistent with the response characteristics of fractured formation.

**Figure 4. The effect of cave filler on the ratio of measurement signals**

3. **Conclusion**

   Using 3D FEM method, the logging responses of LWD resistivity imaging tool in cave formation are simulated. From the results, the following conclusions are drawn.

   1. The borehole has obvious effect on the measured current signal.
   2. The factors of the cave diameter and cave extension have different relationships with ratio of measurement signal. And the relationship depends on the type of cave (medium cave or large cave).
   3. Both the cave diameter and cave extension have a linear relationship and power exponent relationship with ratio of measurement signals respectively when the cave is large cave. Compared with the large cave, the medium cave does not have these certain relationships with ratio of measurement signals.
   4. The relationship between the resistivity contrast and the ratio of measurement current is power exponent no matter the size of the cave is medium or large.

4. **Acknowledgments**

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