Abstract
At present, the method of formation pressure is mainly divided into pressure prediction before drilling, pressure monitoring while drilling, and post-drilling pressure detection. The drilling monitoring method and the post-drilling pressure detection method cannot predict the pressure value of the formation in front of the drill bit. The pre-drilling prediction method is used to predict pressure by seismic data, but the accuracy of the result is not high. How to infer the pressure information of complex and unknown drilling strata based on very limited known formation pressure information is the key technical problem to be solved in this paper. In order to solve this problem, a method based on grey theory is proposed to predict the formation pressure in front of the drill. The prediction results of formation pore pressure based on the method in this paper are compared with the monitoring results of formation pore pressure while drilling: the maximum error is 3.408%, and the average relative error is 3.038%, which indicates that the model has high accuracy. It can meet the requirements of field drilling construction. Through the research of this paper, it can provide more accurate pore pressure information of the formation to be drilled under the bit. Based on the pressure prediction results of the formation to be drilled, dynamic engineering risk assessment can be carried out, so as to assist the drilling operators to make quick and accurate decisions and prevent drilling risk caused by inaccurate understanding of pressure information.

Keywords Pore pressure prediction · Pore pressure monitoring · Grey prediction theory · Drilling safety

Introduction
Formation pressure is the basic data reflecting the fluid situation, rock type, engineering mechanical properties and geological structure in the formation. Accurate prediction of formation pressure is an important prerequisite to ensure the smooth and safe drilling from design to construction (Jiang 2006; Du et al. 1995; Hubbert and Rubey 1959). Therefore, formation pressure monitoring and prediction has always been an important task in oil and gas drilling. At present, the methods of obtaining abnormal formation pressure are mainly divided into the following categories (Chen and Guan 2006): pre-drilling pressure prediction, pressure monitoring while drilling, geophysical logging pressure detection, and pressure measurement. The prediction of pre-drilling pressure is mainly to calculate the formation pore pressure by using the seismic layer velocity data and the relationship model between the formation pore pressure and the formation pore pressure. The commonly employed approaches include (Fillippone 1979, 1982; Ifeanyl 2015; Sayers et al. 2000): equivalent depth method, single point prediction model and comprehensive prediction model, etc. Pressure monitoring with various drilling and logging parameters has been widely used in the actual drilling process of oil and gas fields, which plays a real-time role in guiding drilling engineering (Majidi et al. 2017; Jincai and Shangxian 2017; Emmanuel et al. 2016). Geophysical logging is generally recognized as an important means for accurate prediction of formation pressure. The commonly employed approaches include (Eaton 1975; Bowers 1995; Ben-Awuah et al. 2017; Dutta 2002): shale acoustic time difference method, shale resistivity method, shale density method, etc. However, this
method is a post-prediction method, which cannot predict the pore pressure of the undrilled formation below the bottom of the well. Neither MWD nor PWD can predict the pressure of the formation to be drilled in front of the bit. At present, the prediction method of formation pressure before drilling is to predict formation pressure by seismic data, but the accuracy of prediction results is not high. In addition to the complexity of underground geological conditions, the more important reason is that there is too little information under the bottom of the well, or there is no useful information at all. How to infer the pressure information of the complex and unknown formation to be drilled from the very limited known formation pressure information is the key technical problem to be solved in this paper.

Pore pressure prediction mode in front of bit

Grey prediction theory

(1) Grey prediction method

The theory of grey system was first put forward by Professor Deng Julong of Huazhong University of science and technology in 1982, and then, it has been paid attention to at home and abroad (Wen 2003). The theory of grey system is a subject that takes the uncertain system of “part information is known, part information is unknown” as the research object. Its characteristic is to extract valuable information through the generation and development of “part” known information, to realize the accurate description and effective monitoring of system operation behaviour. “Poor information, small sample system” is the main research content of grey system theory. Through the processing, mining and utilization of the existing “poor information” and through the correct grasp and description of the evolution law of the system operation behaviour, it can realize the recognition of the real world and the prediction of the future state.

(2) Modelling principle of grey prediction model (Xie and Liu 2005; Yang et al. 2011)

Set \( X^{(0)} \) as raw data sequence: \( X^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n)\} \).

\( X^{(1)} \) is a new data sequence generated by first-order accumulation of \( X^{(0)} \):

\[
X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)\}
\]

In formula, \( x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i) (k = 1, 2, \ldots, n) \).

\( Z^{(1)} \) is mean generation with consecutive neighbours of \( X^{(1)} \):

\[
Z^{(1)} = \{z^{(1)}(2), z^{(1)}(3), \ldots, z^{(1)}(n)\}
\]

In formula, \( z^{(1)}(k) = 0.5(x^{(1)}(k) + x^{(1)}(k - 1)), \quad k = 2, 3, \ldots, n \).

Assume the parameters are listed as:

\[
\Phi = [a, b]^T, \quad B = \begin{bmatrix}
-e^{(1)(2)} / 3 \\
\vdots \\
-e^{(1)(n)} / 3
\end{bmatrix},
\]

\[
Y = (x^{(0)}(2), x^{(0)}(3), \ldots, x^{(0)}(n))^T.
\]

The least squares estimation sequence of \( x^{(0)}(k) + a z^{(1)}(k) = b \) is: \( \Phi = [B^T B]^{-1} B^T Y \).

The solution process is as follows:

① The solution of whitening equation \( \frac{dx^{(1)}}{dt} + a x^{(1)} = b \) (also called time response function) is:

\[
x^{(1)}(t) = \left(x^{(1)}(1) - \frac{b}{a}\right) e^{-at} + \frac{b}{a}
\]

② The solution (also called time response series) of \( x^{(0)}(k) + a z^{(1)}(k) = b \) is:

\[
x^{(1)}(k + 1) = \left(x^{(0)}(1) - \frac{b}{a}\right) e^{-ak} + \frac{b}{a}, \quad (k = 1, 2, 3, \ldots, n)
\]

③ Reduction value:

\[
x^{(1)}(k + 1) = \left(x^{(0)}(1) - \frac{b}{a}\right) e^{-ak} + \frac{b}{a}, \quad (k = 1, 2, 3, \ldots, n)
\]

Pore pressure prediction mode

Based on the grey theory, this paper establishes the prediction model of formation pressure while drilling and predicts the formation pressure to be drilled in front of the bit according to the monitoring results of the pressure while drilling in front of the bit. The pressure monitoring results while drilling of the drilled formation within a certain depth of the upper part of the bit position are selected as the initial raw data. In order to reduce the randomness and uncertainty of the original series, the moving average method is used. Then, the differential dynamic equation of the system is constructed by fitting, and the model built according to the new sequence is reduced and generated, and finally the pressure prediction model is established. The steps are as follows:

① Construct primitive sequence

Take the depth of the bit as the origin and take the formation pressure monitoring values of \( n \) points equidistant upward as the original data:

\[
p^{(0)} = \{p^{(0)}(k)\} = \{p^{(0)}(1), p^{(0)}(2), \ldots, p^{(0)}(n)\}, \quad k = 1, 2, \ldots, n.
\]

② Preprocessing the original sequence

The moving average method is applied to preprocess the original sequence:

\[
\Phi = [a, b]^T, \quad B = \begin{bmatrix}
-e^{(1)(2)} / 3 \\
\vdots \\
-e^{(1)(n)} / 3
\end{bmatrix},
\]

\[
Y = (x^{(0)}(2), x^{(0)}(3), \ldots, x^{(0)}(n))^T.
\]
④ Solve restore model
Square method. The solution is as follows:

\[
\begin{align*}
\Delta(p(0)) &= \{ p^{(0)}(1), p^{(0)}(2), \ldots, p^{(0)}(n) \}, \quad k = 1, 2, \ldots, n. \tag{5}
\end{align*}
\]

\[
\begin{align*}
p^{(0)}(1) &= \frac{3p^{(0)}(1) + \nu p^{(0)}(2)}{4} \\
p^{(0)}(n) &= \frac{p^{(0)}(n-1) + \nu p^{(0)}(n)}{4} \\
p^{(0)}(k) &= \frac{p^{(0)}(k-1) + 2p^{(0)}(k) + p^{(0)}(k+1)}{4}, \quad k = 2, \ldots, n-1. \tag{6}
\end{align*}
\]

⑤ Building grey model GM (1, 1)
Make 1-AGO (first order accumulation) of \( p^{(0)} \) to get the generating sequence:

\[
p^{(1)} = \{ p^{(1)}(1), \ldots, p^{(1)}(n) \}, \quad k = 1, 2, \ldots, n. \quad \text{In formula,} \quad p^{(1)}(k) = \sum_{j=1}^{k} p^{(0)}(j).
\]

The mean value of \( p^{(1)} \) is processed, and its generating sequence is:

\[
\zeta^{(1)} = \{ \zeta^{(1)}(k) \} = \{ \nu^{(1)}(1), \zeta^{(1)}(2), \ldots, \zeta^{(1)}(n) \}, \quad k = 1, 2, \ldots, n.
\]

In formula, \( \zeta^{(1)}(k) = 0.5[p^{(1)}(k) + p^{(1)}(k-1)] \). Establish the grey differential equation:

\[
\begin{align*}
\frac{dp^{(1)}}{dk} + ap^{(1)} &= b.
\end{align*}
\]

(7)

Using the grey differential equation, the coefficient \( a, b \) are calculated:

\[
p^{(1)}(k) = a\zeta^{(1)}(k) = b.
\]

(8)

Substituting coefficient into grey differential equation.
The coefficient is substituted into the grey differential equation, and the equation is solved according to the least square method. The solution is as follows:

\[
\Delta p^{(1)}(k+1) = \left( p^{(0)}(1) - \frac{b}{a} \right) e^{-ak} + \frac{b}{a}.
\]

(9)

⑥ Solve restore model
Making I-IAGO for \( \Delta p^{(1)} \) to get the reduction model

\[
\Delta p^{(0)}(k+1) = -a\left( p^{(0)}(1) - \frac{b}{a} \right) e^{-ak} \]

\[
\bar{p}^{(0)}(k+1) = \bar{p}^{(0)}(k) + \Delta p^{(0)}(k+1) \bar{p}^{(1)}(k)
\]

(10)

When \( k = 1, 2, \ldots, n-1 \), the simulated value \( \bar{p}^{(0)} \) of the original sequence \( p^{(0)} \) can be obtained.

⑦ Carry out residual inspection
Set \( \Delta(k) \) as the residual value, \( e(k) \) the relative residual value, and \( q \) the average precision:

\[
\Delta(k) = p^{(0)}(k) - \bar{p}^{(0)}(k), e(k) = \Delta(k)/p^{(0)}(k) \]

(11)

\[
q = \left(1 - \frac{1}{n-1} \sum_{k=2}^{n} |e(k)| \right) \times 100% \tag{12}
\]

If the average precision \( q \) is greater than 90%, it means that the sequence meets the requirements of modelling and can be predicted. Otherwise, repeat steps ① to ⑤ until the conditions are met.

⑧ Prediction of pore pressure in front of bit
After the accuracy meets the requirements, predict the pore pressure in front of bit:

\[
\bar{p}^{(0)} = \left\{ \bar{p}^{(0)}(1), \bar{p}^{(0)}(2), \ldots, \bar{p}^{(0)}(n), \bar{p}^{(0)}(n+1) \right\}
\]

(13)

Remove the monitoring data of formation pressure while drilling at the top first point, add the predicted pressure value \( \bar{p}^{(0)}(n+1) \) into the original sequence, and update the original data of formation pressure as follows:

\[
\bar{p}^{(0)} = \left\{ \bar{p}^{(0)}(2), \bar{p}^{(0)}(3), \ldots, \bar{p}^{(0)}(n+1) \right\}
\]

(14)

Using the new original formation pressure series \( p^{(0)} \), the next adjacent point’s formation pressure prediction can be started again. The prediction diagram of pore pressure in front of bit based on grey theory is shown in Fig. 1.

Case calculation and result analysis
In this paper, XX well is selected as an example for calculation and result analysis. The lithology is mainly fine-grained sediment. The porosity is generally 0.84–2.24%, with an average of 1.41%. The permeability is mainly 0.02–0.14md. The buried depth of the reservoir is about 3500 m, the temperature gradient is 2.86–3.12 °C/100 M, and the pressure coefficient is 1.8–2.1. The prediction results of pre-drilling pressure in XX well show that: the pressure coefficient fluctuates between 1.0 and 1.2 before 1500 m, which belongs to the normal hydrostatic pressure system; but from 1500 m to below, the pressure starts to rise gradually. The existence of abnormal high pressure seriously affects drilling safety. Therefore, pressure monitoring while drilling is carried out in the well section with a depth of 1500 m, and the results are shown in Fig. 2. At this time, the bit position is 1750 m. The drilling fluid is oil-based, with the density of 1.65 g/cm³ and the displacement of about 40 L/s. Firstly, according to the real-time monitoring data of drilling, the monitoring results of formation pore pressure in the upper 1700–1749 m well section of the bit are calculated as the original sequence, and the pressure of 1750–1759 m in front of the bit is predicted by the grey prediction method established in this paper. The specific steps are shown in Fig. 3.
Fig. 1 Sketch map of formation pressure prediction in front of bit based on grey theory

Fig. 2 Variation of interval transit time, resistivity and pore pressure with depth of XX well
First of all, 1700–1749 m formation pressure monitoring data while drilling is selected as the original sequence, as shown in Table 1.

Set the original data sequence of formation pressure as: 
\[ Z^{(1)} = \{ z^{(1)}(k) \} = \{ z^{(1)}(1), z^{(1)}(2), \ldots, z^{(1)}(50) \}, \quad k = 1, 2, \ldots, 50. \]

The prediction model of formation pressure while drilling is established by using 50 groups of monitoring data series of formation pressure while drilling with the help of grey system theory modelling software (Gtms3.0) and MATLAB software. Using the grey system theory modelling software to do the first-order immediate generating sequence, the results are shown in Table 2. The first-order immediate generating sequence is substituted into the smooth sequence judgment condition, which satisfies the smooth sequence condition. The first-order accumulation generation (1-AGO) is made for the original data sequence, and the results are shown in Table 3.

It can be seen from Table 3 that the first-order accumulation generation sequence of formation pressure is a non-negative increasing sequence with good smoothness. According to the above two steps, it can be judged that the original data sequence of formation pressure has a good smoothness ratio,

### Table 1 Monitoring data of formation pore pressure during drilling from 1700 to 1749 m

| Depth (m) | \( P_p \) coefficient | Depth (m) | \( P_p \) coefficient | Depth (m) | \( P_p \) coefficient | Depth (m) | \( P_p \) coefficient | Depth (m) | \( P_p \) coefficient |
|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|
| 1700      | 1.4434                 | 1710      | 1.4673                 | 1720      | 1.4675                 | 1730      | 1.4586                 | 1740      | 1.4521                 |
| 1701      | 1.4452                 | 1711      | 1.4675                 | 1721      | 1.4665                 | 1731      | 1.4582                 | 1741      | 1.4515                 |
| 1702      | 1.4468                 | 1712      | 1.4683                 | 1722      | 1.4650                 | 1732      | 1.4577                 | 1742      | 1.4504                 |
| 1703      | 1.4488                 | 1713      | 1.4689                 | 1723      | 1.4636                 | 1733      | 1.4568                 | 1743      | 1.4493                 |
| 1704      | 1.4512                 | 1714      | 1.4695                 | 1724      | 1.4621                 | 1734      | 1.4564                 | 1744      | 1.4433                 |
| 1705      | 1.4533                 | 1715      | 1.4696                 | 1725      | 1.4608                 | 1735      | 1.4556                 | 1745      | 1.4425                 |
| 1706      | 1.4621                 | 1716      | 1.4697                 | 1726      | 1.4597                 | 1736      | 1.4548                 | 1746      | 1.4419                 |
| 1707      | 1.4644                 | 1717      | 1.4695                 | 1727      | 1.4590                 | 1737      | 1.4543                 | 1747      | 1.4412                 |
| 1708      | 1.4674                 | 1718      | 1.4690                 | 1728      | 1.4588                 | 1738      | 1.4535                 | 1748      | 1.4403                 |
| 1709      | 1.4689                 | 1719      | 1.4686                 | 1729      | 1.4587                 | 1739      | 1.4529                 | 1749      | 1.4393                 |
so it can be substituted into the grey system theory modeling software and combined with MATLAB software for modelling and prediction. The specific steps are as follows:

**Step 1:** Initialization of original formation pressure data and enumeration of original formation pressure data series.

**Step 2:** The 1-AGO sequence of the original data sequence is generated, as shown in Table 3.

**Step 3:** First order immediate generating sequence of 1-AGO, as shown in Table 4.

**Step 4:** Calculation of prediction model coefficient, \( a = 0.0003, b = 1.4672 \).

**Step 5:** Calculation of pore pressure simulation value, the results are shown in Table 5.

**Step 6:** The residual is 0.0028. The relative average error of formation pressure prediction model is:

\[
q = \left(1 - \frac{1}{n-1} \sum_{k=2}^{n} |\epsilon(k)|\right) \times 100\% = 99.6084\% > 90\%.
\]

**Step 7:** According to the established model, the formation pressure in the next ten steps (the front part of the bit is not

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**Table 2** First order immediate generating sequence of pore pressure

| Serial | FOIG | Serial | FOIG | Serial | FOIG | Serial | FOIG |
|--------|------|--------|------|--------|------|--------|------|
| 1      | 1.4400 | 11     | 1.4680 | 21     | 1.4685 | 31     | 1.4590 |
| 2      | 1.4440 | 12     | 1.4675 | 22     | 1.4670 | 32     | 1.4585 |
| 3      | 1.4460 | 13     | 1.4680 | 23     | 1.4655 | 33     | 1.4580 |
| 4      | 1.4480 | 14     | 1.4685 | 24     | 1.4645 | 34     | 1.4575 |
| 5      | 1.4500 | 15     | 1.4690 | 25     | 1.4630 | 35     | 1.4565 |
| 6      | 1.4520 | 16     | 1.4695 | 26     | 1.4615 | 36     | 1.4560 |
| 7      | 1.4575 | 17     | 1.4700 | 27     | 1.4605 | 37     | 1.4555 |
| 8      | 1.4630 | 18     | 1.4700 | 28     | 1.4595 | 38     | 1.4545 |
| 9      | 1.4655 | 19     | 1.4695 | 29     | 1.4590 | 39     | 1.4535 |
| 10     | 1.4680 | 20     | 1.4690 | 30     | 1.4590 | 40     | 1.4530 |

**Table 3** First-order cumulative generating sequence of pore pressure (1-AGO)

| Serial | 1-AGO | Serial | 1-AGO | Serial | 1-AGO | Serial | 1-AGO | Serial | 1-AGO |
|--------|-------|--------|-------|--------|-------|--------|-------|--------|-------|
| 1      | 1.4434 | 11     | 16.0188 | 21     | 30.7069 | 31     | 45.3197 | 41     | 59.872 |
| 2      | 2.8886 | 12     | 17.4863 | 22     | 32.1734 | 32     | 46.7779 | 42     | 61.3235 |
| 3      | 4.3354 | 13     | 18.9546 | 23     | 33.6384 | 33     | 48.2356 | 43     | 62.7739 |
| 4      | 5.7842 | 14     | 20.4235 | 24     | 35.102  | 34     | 49.6924 | 44     | 64.2232 |
| 5      | 7.2354 | 15     | 21.893  | 25     | 36.5641 | 35     | 51.1488 | 45     | 65.6665 |
| 6      | 8.6887 | 16     | 23.3626 | 26     | 38.0249 | 36     | 52.6044 | 46     | 67.109 |
| 7      | 10.1508| 17     | 24.8323 | 27     | 39.4846 | 37     | 54.0592 | 47     | 68.5509 |
| 8      | 11.6152| 18     | 26.3018 | 28     | 40.9436 | 38     | 55.5135 | 48     | 69.9921 |
| 9      | 13.0826| 19     | 27.7708 | 29     | 42.4024 | 39     | 56.967  | 49     | 71.4324 |
| 10     | 14.5515| 20     | 29.2394 | 30     | 43.8611 | 40     | 58.4199 | 50     | 72.8717 |

**Table 4** First-order immediate generating sequence of pore pressure (1-AGO)

| Serial | 1-AGO FOIG | Serial | 1-AGO FOIG | Serial | 1-AGO FOIG | Serial | 1-AGO FOIG | Serial | 1-AGO FOIG |
|--------|------------|--------|------------|--------|------------|--------|------------|--------|------------|
| 1      | 1.4434     | 11     | 15.2852    | 21     | 29.9732    | 31     | 44.5904    | 41     | 59.1459    |
| 2      | 2.1660     | 12     | 16.7526    | 22     | 31.4402    | 32     | 46.0488    | 42     | 60.5977    |
| 3      | 3.6120     | 13     | 18.2205    | 23     | 32.9059    | 33     | 47.5068    | 43     | 62.0487    |
| 4      | 5.0598     | 14     | 19.6891    | 24     | 34.3702    | 34     | 48.9641    | 44     | 63.4985    |
| 5      | 6.5098     | 15     | 21.1583    | 25     | 35.8331    | 35     | 50.4206    | 45     | 64.9448    |
| 6      | 7.9621     | 16     | 22.6278    | 26     | 37.2945    | 36     | 51.8766    | 46     | 66.3877    |
| 7      | 9.4197     | 17     | 24.0975    | 27     | 38.7548    | 37     | 53.3318    | 47     | 67.8299    |
| 8      | 10.8831    | 18     | 25.5671    | 28     | 40.2141    | 38     | 54.7864    | 48     | 69.2715    |
| 9      | 12.3489    | 19     | 27.0363    | 29     | 41.6731    | 39     | 56.2403    | 49     | 70.7122    |
| 10     | 13.8171    | 20     | 28.5051    | 30     | 43.1318    | 40     | 57.6935    | 50     | 72.1521    |
drilled 1750–1759 m) is predicted and compared with the formation pressure monitoring results while drilling. The results are shown in Table 6.

Comparing the prediction results of formation pore pressure in 1750–1759 m well section based on grey theory with the monitoring results of formation pore pressure while drilling, it is found that: the maximum relative error is 3.408%, and the average relative error is 3.038%. It shows that the model has high accuracy and can accurately predict the formation pore pressure 10 m below the bit, which can meet the requirements of field drilling construction.

### Conclusions and suggestions

A. The methods of obtaining formation pressure are mainly divided into pre-drilling pressure prediction, pressure monitoring while drilling, geophysical logging pressure detection, and pressure measurement. Neither MWD nor PWD can predict the pressure of the formation to be drilled in front of the bit. The prediction method of formation pressure before drilling is to predict formation pressure by seismic data, but the accuracy of prediction result is not high.

B. In this paper, the grey prediction theory is applied to predict the pore pressure of the formation to be drilled in front of the bit in the process of drilling, and a pressure prediction model is constructed, and an example is applied. The results show that: the maximum relative error is 3.408%, and the average relative error is 3.038%. It shows that the model has high precision and can meet the requirements of drilling construction.

C. Through the research of this paper, it can provide more accurate pore pressure information of the formation to be drilled under the bit. Based on the pressure prediction results of the formation to be drilled, dynamic engineering risk assessment can be carried out, so as to assist the drilling operators to make quick and accurate decisions and prevent drilling risk caused by inaccurate understanding of pressure information.

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**Table 5** Simulation value of pore pressure

| Serial | Result | Serial | Result | Serial | Result | Serial | Result | Serial | Result |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1      | 1.4432 | 11     | 1.4633 | 21     | 1.4595 | 31     | 1.4558 | 41     | 1.4521 |
| 2      | 1.4666 | 12     | 1.4629 | 22     | 1.4591 | 32     | 1.4554 | 42     | 1.4518 |
| 3      | 1.4662 | 13     | 1.4625 | 23     | 1.4588 | 33     | 1.4551 | 43     | 1.4514 |
| 4      | 1.4658 | 14     | 1.4621 | 24     | 1.4584 | 34     | 1.4547 | 44     | 1.4510 |
| 5      | 1.4654 | 15     | 1.4617 | 25     | 1.4580 | 35     | 1.4543 | 45     | 1.4507 |
| 6      | 1.4651 | 16     | 1.4614 | 26     | 1.4577 | 36     | 1.4540 | 46     | 1.4503 |
| 7      | 1.4647 | 17     | 1.4610 | 27     | 1.4573 | 37     | 1.4536 | 47     | 1.4499 |
| 8      | 1.4643 | 18     | 1.4606 | 28     | 1.4569 | 38     | 1.4532 | 48     | 1.4492 |
| 9      | 1.4640 | 19     | 1.4603 | 29     | 1.4566 | 39     | 1.4529 | 49     | 1.4495 |
| 10     | 1.4636 | 20     | 1.4599 | 30     | 1.4562 | 40     | 1.4525 | 50     | 1.4488 |

**Table 6** The error between formation pressure prediction value and monitoring value

| Serial | Depth (m) | $P_p$ prediction value | PWD | Error % |
|--------|-----------|------------------------|-----|---------|
| 1      | 1750      | 1.4785                 | 1.4356 | 2.901  |
| 2      | 1751      | 1.4881                 | 1.4373 | 3.408  |
| 3      | 1752      | 1.4897                 | 1.4391 | 3.392  |
| 4      | 1753      | 1.4883                 | 1.4391 | 3.303  |
| 5      | 1754      | 1.4847                 | 1.4376 | 3.171  |
| 6      | 1755      | 1.4796                 | 1.4362 | 2.933  |
| 7      | 1756      | 1.4782                 | 1.4354 | 2.891  |
| 8      | 1757      | 1.4768                 | 1.4342 | 2.881  |
| 9      | 1758      | 1.4755                 | 1.4342 | 2.798  |
| 10     | 1759      | 1.4745                 | 1.4346 | 2.699  |
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