Journal of Petroleum Exploration and Production Technology (2020) 10:2439–2446
https://doi.org/10.1007/s13202-020-00896-3

ORIGINAL PAPER -EXPLORATION ENGINEERING

Pore pressure prediction in front of drill bit based on grey prediction theory

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Received: 14 January 2020 / Accepted: 28 April 2020 / Published online: 9 May 2020

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

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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: $X^{(0)}=\left\{x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)\right\}$.

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

$X^{(1)}=\left\{x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)\right\}$. In formula, $x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i) (k = 1, 2, \dots, n)$.

$Z^{(1)}$ is mean generation with consecutive neighbours of $X^{(1)}$.

$Z^{(1)}=\left\{z^{(1)}(2), z^{(1)}(3), \dots, z^{(1)}(n)\right\}$.

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

Assume the parameters are listed as:

$$\boldsymbol{\Phi} = [a, b]^{\mathrm{T}}, \text{ and } B = \begin{bmatrix} -z^{(1)}(2)1 \\ -z^{(1)}(3)1 \\ \vdots \\ -z^{(1)}(n)1 \end{bmatrix},$$

$$Y = \left(x^{(0)}(2), x^{(0)}(3), \dots, x^{(0)}(n)\right)^{\mathrm{T}}.$$

The least squares estimation sequence of $x^{(0)}(k) + az^{(1)}(k) = b$ is: $\overline{\boldsymbol{\Phi}} = \left[B^{\mathrm{T}}B\right]^{-1}B^{\mathrm{T}}Y$.

The solution process is as follows:

① The solution of whitening equation $\frac{\mathrm{d}x^{(1)}}{\mathrm{d}t} + ax^{(1)} = b$ (also called time response function) is:

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

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

$$\hat{x}^{(1)}(k+1) = \left(x^{(0)}(1) - \frac{b}{a}\right)e^{-ak} + \frac{b}{a}, \quad (k = 1, 2, 3, \dots, n) \tag{2}$$

③ Reduction value:

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

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:

$$p^{(0)} = \left\{p^{(0)}(k)\right\} = \left\{p^{(0)}(1), p^{(0)}(2), \dots, p^{(0)}(n)\right\}, \quad k = 1, 2, \dots, n. \tag{4}$$

② Preprocessing the original sequence

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

$$p'^{(0)} = \{p'^{(0)}(k)\} = \{p'^{(0)}(1), p'^{(0)}(2), \ldots, p'^{(0)}(n)\}, \quad k = 1, 2, \ldots, n. \tag{5}$$

$$\begin{cases} p'^{(0)}(1) = \dfrac{3p^{(0)}(1) + p'^{(0)}(2)}{4} \\ p'^{(0)}(n) = \dfrac{p^{(0)}(n-1) + 3p^{(0)}(n)}{4} \\ p'^{(0)}(k) = \dfrac{p^{(0)}(k-1) + 2p^{(0)}(k) + p'^{(0)}(k+1)}{4}, \quad k = 2, \ldots, n-1. \end{cases} \tag{6}$$

③ Building grey model GM (1, 1)

Make 1-AGO (first order accumulation) of $p'^{(0)}$ to get the generating sequence:

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

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

$$z^{(1)} = \{z^{(1)}(k)\} = \{z^{(1)}(1), z^{(1)}(2), \ldots, z^{(1)}(n)\}, \quad k = 1, 2, \ldots, n.$$

In formula, $z^{(1)}(k) = 0.5\left[p^{(1)}(k) + p^{(1)}(k-1)\right]. \quad k = 2, \ldots, n.$

Establish the grey differential equation:

$$\frac{dp^{(1)}}{dk} + ap^{(1)} = b \tag{7}$$

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

$$p^{(1)}(k) = az^{(1)}(k) = b \tag{8}$$

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:

$$\overline{p}^{(1)}(k+1) = \left(p'^{(0)}(1) - \frac{b}{a}\right)e^{-ak} + \frac{b}{a} \tag{9}$$

④ Solve restore model

Making 1-IAGO for $\overline{p}^{(1)}$ to get the reduction model

$$\begin{aligned} \overline{p}^{(0)}(k+1) &= -a\left(p'^{(0)}(1) - \frac{b}{a}\right)e^{-ak} \\ \overline{p}^{(0)}(k+1) &= \overline{p}^{(1)}(k+1) - \overline{p}^{(1)}(k) \end{aligned} \tag{10}$$

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

⑤ Carry out residual inspection

Set $\Delta(k)$ as the residual value, $\varepsilon(k)$ the relative residual value, and q the average precision:

$$\Delta(k)^{(0)} = p'^{(0)}(k) - \overline{p}^{(0)}(k), \varepsilon(k)^{(0)} = \Delta(k)^{(0)} / p'^{(0)}(k) \tag{11}$$

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

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.

⑥ Prediction of pore pressure in front of bit

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

$$\overline{p}^{(0)} = \left\{\overline{p}^{(0)}(1), \overline{p}^{(0)}(2), \ldots \overline{p}^{(0)}(n), \overline{p}^{(0)}(n+1)\right\} \tag{13}$$

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

$$p^{*(0)} = \left\{p'^{(0)}(2), p'^{(0)}(3), \ldots, \overline{p}^{(0)}(n+1)\right\} \tag{14}$$

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/cm^3 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.

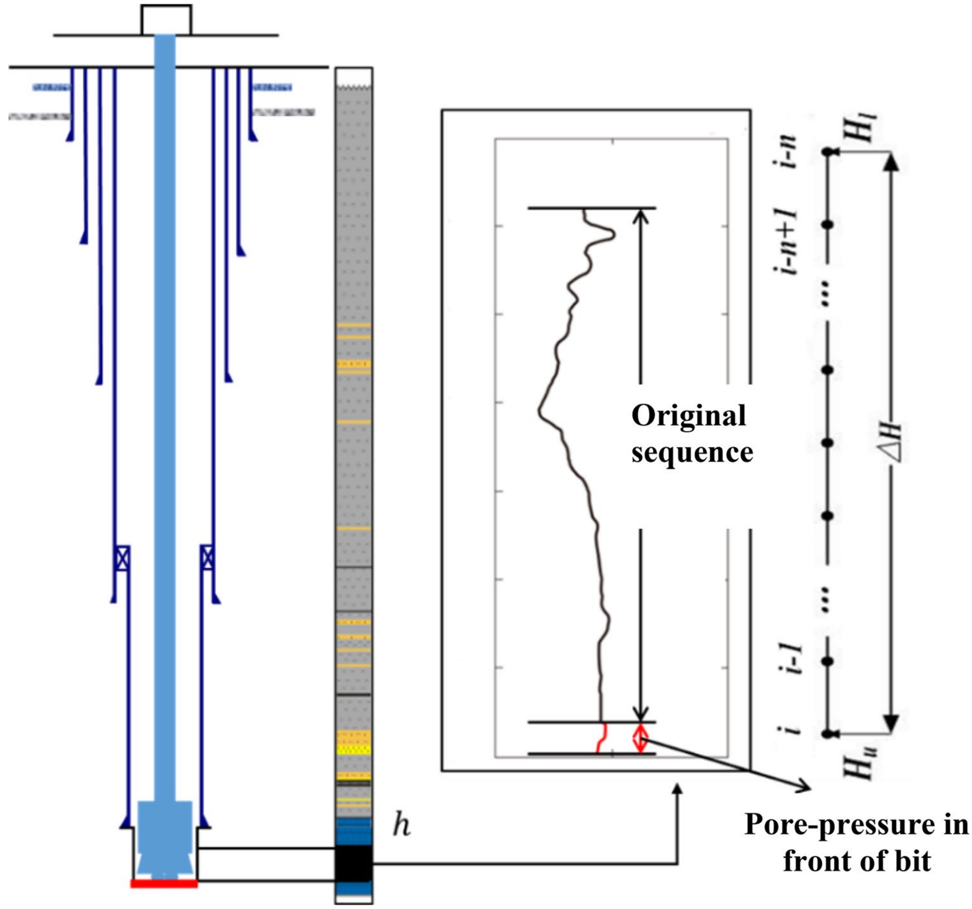

Fig. 1 Sketch map of formation pressure prediction in front of bit based on grey theory

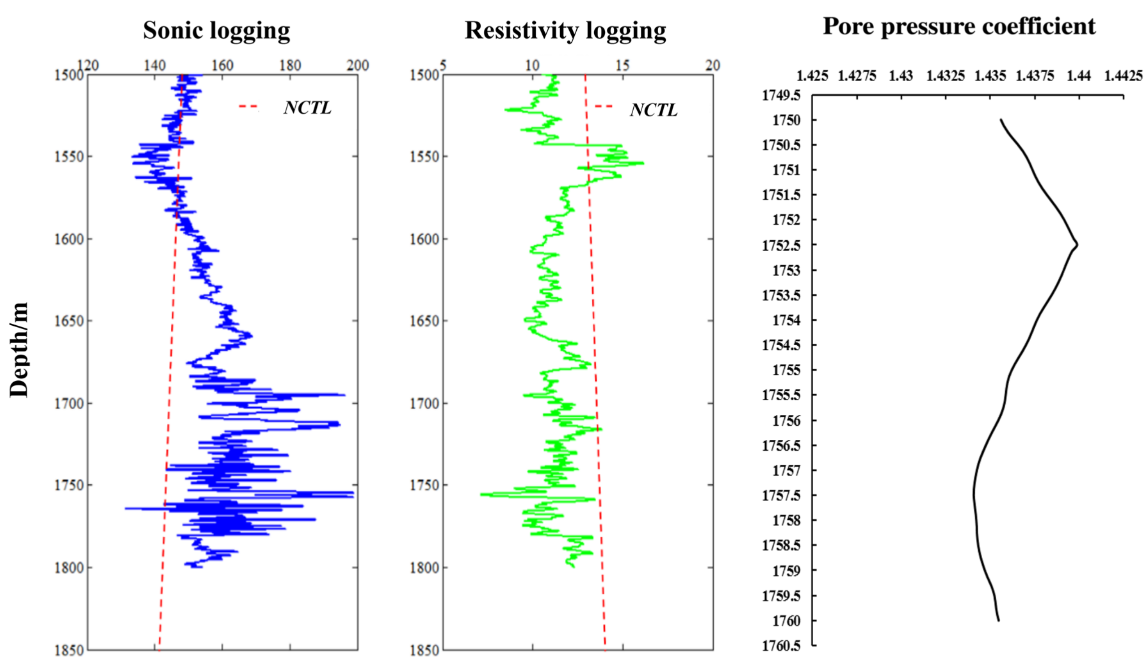

Fig. 2 Variation of interval transit time, resistivity and pore pressure with depth of XX well

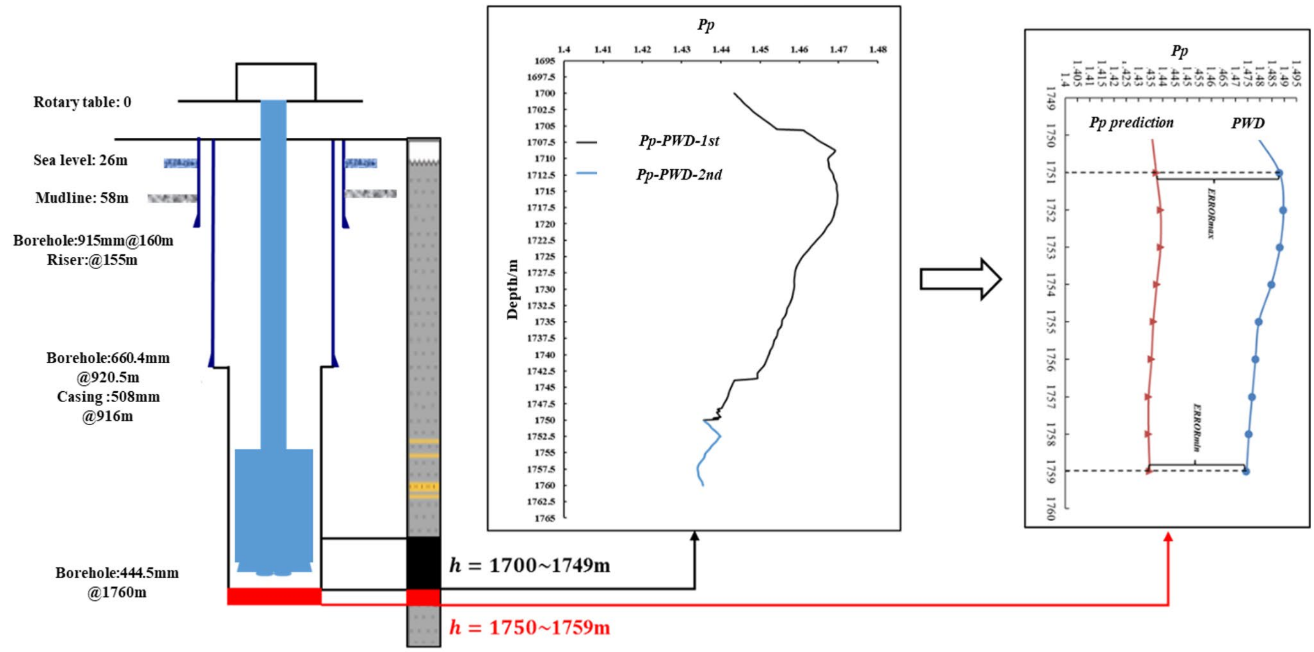

Fig. 3 Flow chart of pressure prediction 10 m in front of bit at 1750 m

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:

$$P^{(0)} = \left\{p^{(0)}(k)\right\} = \left\{p^{(0)}(1), p^{(0)}(2), \dots, p^{(0)}(50)\right\}, \quad k = 1, 2, \dots, 50.$$

$Z^{(1)}$ is mean generation with consecutive neighbours of P:

$$z^{(1)} = \left\{z^{(1)}(k)\right\} = \left\{z^{(1)}(1), z^{(1)}(2), \dots, z^{(1)}(50)\right\}, \quad k = 1, 2, \dots, 50.$$

In formula, $z^{(1)}(k) = 0.5\left[p^{(1)}(k) + p^{(1)}(k-1)\right], \quad k = 2, \dots, 50.$

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 modelling 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: $q = \left(1 - \frac{1}{n-1}\sum_{k=2}^{n} |\varepsilon(k)|\right) \times 100\% = 99.6084\% > 90\%$.

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

Table 2 First order immediate generating sequence of pore pressure

Serial	FOIG	Serial	FOIG	Serial	FOIG	Serial	FOIG	Serial	FOIG
1	1.4400	11	1.4680	21	1.4685	31	1.4590	41	1.4525
2	1.4440	12	1.4675	22	1.4670	32	1.4585	42	1.4515
3	1.4460	13	1.4680	23	1.4655	33	1.4580	43	1.4505
4	1.4480	14	1.4685	24	1.4645	34	1.4575	44	1.4495
5	1.4500	15	1.4690	25	1.4630	35	1.4565	45	1.4460
6	1.4520	16	1.4695	26	1.4615	36	1.4560	46	1.4425
7	1.4575	17	1.4700	27	1.4605	37	1.4555	47	1.4420
8	1.4630	18	1.4700	28	1.4595	38	1.4545	48	1.4415
9	1.4655	19	1.4695	29	1.4590	39	1.4535	49	1.4405
10	1.4680	20	1.4690	30	1.4590	40	1.4530	50	1.4395

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

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

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.

Acknowledgements The authors would like to acknowledge the academic and technical support of Drilling Engineering and Technology Research Institute, Zhongyuan Petroleum Engineering Co., Ltd., SINOPEC. This paper is supported by Program for Sinopec Petroleum Engineering Technology Service Co., Ltd. project "Research on measurement technology of downhole drilling string engineering parameters". Contract No.: SG 17-12 k. Post-doctoral project of Sinopec Zhongyuan Petroleum Engineering Company "Research on risk assessment and early warning technology of South Sichuan shale gas drilling project".

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