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A Novel Borehole Cataloguing Method Based on a Drilling Process Monitoring (DPM) System

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Abstract: Borehole cataloguing is an important task in geological drilling. Traditional manual cataloguing provides the stratification of underground boreholes based on changes in core lithology. This paper proposes a novel borehole cataloguing method using a drilling process monitoring (DPM) system. This DPM cataloguing method stratifies a borehole according to the drilling speed through the rock. A 102 m borehole was drilled and cored in Baota district, Yan'an city, Shaanxi Province, China. The rock-breaking response parameters of the drill bit displacement, drill rod rotation speed and inlet pipe and outlet pipe oil pressures were monitored throughout the drilling process, and the drilling depth-penetration rate curve during the net drilling process was obtained. The changes in drilling speed show that the DPM cataloguing can identify the depths of the layer interfaces of the borehole and describe the stratification. The interface depth values obtained by DPM have little difference from the interface depth values obtained by manual cataloguing, and the errors are between −0.04% and 4.29%. From the DPM stratification results, the engineering quality evaluation of the rock mass can be realized without coring. DPM is fast, convenient, accurate, can greatly improve the efficiency of existing catalogues, and can be applied to scientific research in any underground space. DPM is a measurement-while-drilling technology. According to DPM data, the operating state of a drilling rig and the parameter changes while drilling can be obtained in situ and in real time throughout the drilling process.

Keywords: geological drilling; borehole cataloguing; drilling process monitoring; engineering quality; rock mass; engineering management

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1. Introduction

Borehole cataloguing is an important task in drilling. It can provide real and effective information for evaluating the properties of rock and soil and determining the location of ore deposits, and has guiding significance for engineering, construction and mining design [1–5]. In general, during geotechnical engineering borehole recording, the recorder determines the drilling depth by measuring the length of the drill rods and the length of the residual rule each time. For coring drilling projects, it is also necessary to record the lithology and the corresponding drilling depth. However, due to the difficult drilling conditions encountered in situ, the variability in drilling personnel quality, and the difficulty of drilling production management, the current borehole cataloguing quality is low [6,7]. For example, when determining the core lithology and the corresponding depth, the recorder generally uses the cumulative length of the drill rods to identify the interfaces of different lithologies, so the identified interface depths may easily include human error.

In response to the above problems, some scholars have studied new cataloguing devices or methods to improve manual cataloguing. For example, some scholars have designed semiautomatic drilling rig devices. On the one hand, such devices can stabilize the drilling rig and effectively provide shock absorption and lateral support; on the other hand, they can be combined with the programmable controller to achieve smooth hydraulic transmission, which can greatly improve the efficiency of drilling cataloguing [8–11]. Some scholars can establish dynamic links with a large amount of physical logging data through the existing spatial geographic information system data, greatly improving the efficiency of data classification [12,13]. In addition, some borehole cataloguing methods based on mobile technology enable various borehole data to be entered and managed in a unified manner, which improves cataloguing efficiency [14–16]. Some scholars have also proposed a hyperspectral core cataloguing method to semi-quantitatively catalogue core alteration mineral information [17,18]. In the published literature, the extracted cores are catalogued with only a few cataloguing devices or methods, and in-situ cataloguing of the cores cannot be achieved. Measurement-while-drilling technology is closely related to the drilling process, and has not yet been applied to drilling cataloguing. However, it has been found that these new cataloguing devices or methods have the following three problems: (1) Borehole cataloguing often only records drilling depth or lithology information, for example, while ignoring the drilling rig's rock-breaking response information during the drilling process, resulting in a waste of data. (2) Measurement-while-drilling technology in oil wells uses a depth sequence to monitor and collect the rock-breaking response information of the drilling rig. The drilling time cannot correspond to the working status of the drilling rig (drilling, shutdown, hollow drilling, etc.), which has an impact on the quality management of drilling projects. (3) Manual cataloguing tends to overlook the structural planes or weak zones with small thicknesses, which will affect the determination of the boundaries of the drilled geological bodies.

To overcome the shortcomings of the data collection method using a traditional drilling monitoring system, a team led by Yue developed and manufactured the drilling process monitoring (DPM) system [19,20]. A DPM system is a new type of measurement-while-drilling system, which uses time series to monitor and collect rock-breaking response information throughout the process of drilling, which cannot be achieved by other measurement-while-drilling systems. This system monitors and collects parameters such as drill bit displacement, drill rod rotation speed, and oil inlet and outlet oil pressures of the drilling rig based on time series (not depth series). By analyzing the collected data, the drilling depth–time curve of the net drilling process is obtained, the slope of which is the penetration rate [21]. Figure 1 is a schematic diagram of the DPM system installed on the drilling rig without damage. It consists of two units: a sensor unit and a data acquisition unit. The sensor unit refers to the sensor installed on the drilling rig or the console to monitor the response information of the drilling rig's rock-breaking, mainly including displacement sensors, speed sensors, torque sensors and oil pressure sensors. The data acquisition unit is used to receive the electrical signal from the sensor, control the sampling frequency, and display and save the monitoring data in real time. The DPM system can be installed on any drilling rig, and it is not affected by the possible sticking, leakage, and strong vibration of the drilling rig during the drilling process.

In the past twenty years, the DPM system has been extensively studied in the field of geotechnical engineering drilling and surveying and has been mainly used to evaluate the engineering quality of underground rock and soil and identify the degree of stratum weathering. Since 1998, some scholars have used the DPM system to evaluate the engineering quality of volcanic rock formations in Hong Kong and assess the degree of weathering of a formation (boulder, fully weathered, strongly weathered, weakly weathered, slightly weathered, fresh, etc.) [22–24]. Some scholars have used the drilling curve to identify the rock mass interface of a borehole more than ten meters deep and can accurately find a collapsed hole area or weak area throughout the drilling process [25–32]. In addition, some scholars have studied drilling parameters and proposed indicators to identify the engineering quality of underground rock and soil, such as the drilling index [23], drilling rate per unit energy [33], and drilling-specific work [34]. In short, DPM technology enables researchers to quickly, effectively, quantitatively and objectively measure or calculate the size, strength and distribution of rock blocks, as well as the occurrence, extension, unevenness, and thickness of the interface section between them and the physical and mechanical properties of filling material [35].

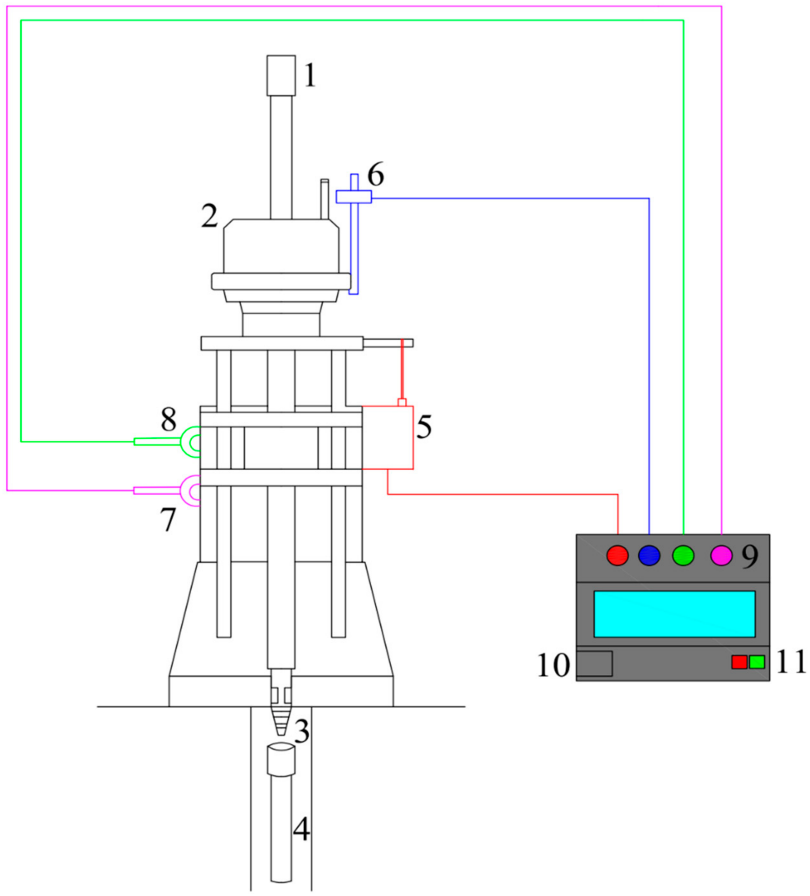

Figure 1. Schematic diagram of the DPM system installed on a drilling rig. 1–4 are some parts of the drilling rig (1: Drill rod; 2: Drill chuck; 3: Drill bit; 4: Coring Rod) and 5–11 are various parts of the DPM system (5: Displacement Sensor; 6: Rotation Sensor; 7: Oil Pressure Sensor for Oil Inlet Pipe; 8: Oil Pressure Sensor for Oil Outlet Pipe; 9: Data module; 10: Indicator; 11: Wireless transmission module).

This article adopts the DPM system to propose a novel cataloguing method. To develop the DPM cataloguing method, this paper uses the DPM system to mount a 102 m borehole in Yan'an city to monitor and collect the rock-breaking response information of the drilling rig, including parameters such as drill bit displacement, drill rod rotation speed, and oil pressure in the inlet and outlet pipes and compares the results of DPM cataloguing with manual cataloguing. The drilling data are analyzed, the drilling depth–time curve of the net drilling process is drawn, and the penetration rates are obtained. According to the penetration rates determined by DPM, the drilled stratum is catalogued.

2. Methodology

This paper proposes a new method of borehole cataloguing based on the borehole process monitoring system. The method is mainly divided into three steps, namely, field drilling experiments, collection of DPM data, and analysis of the net drilling process and drilling speed zones. By exporting the data while drilling, the rock breaking response information for the whole drilling process can be obtained. Therefore, the corresponding drilling rig operating states under the different changes in the rock-breaking response information can be determined and used for drilling engineering management. Through the drilling speed drilling depth map, the drilling speed stratification of the borehole can be obtained. That is to say, the change in the underground geotechnical engineering properties of the borehole can be evaluated. A flowchart of the DPM cataloging method is shown in Figure 2. In this paper, the DPM cataloguing method is applied to a borehole in Yan'an city, Shaanxi Province, and the cataloguing results are studied.

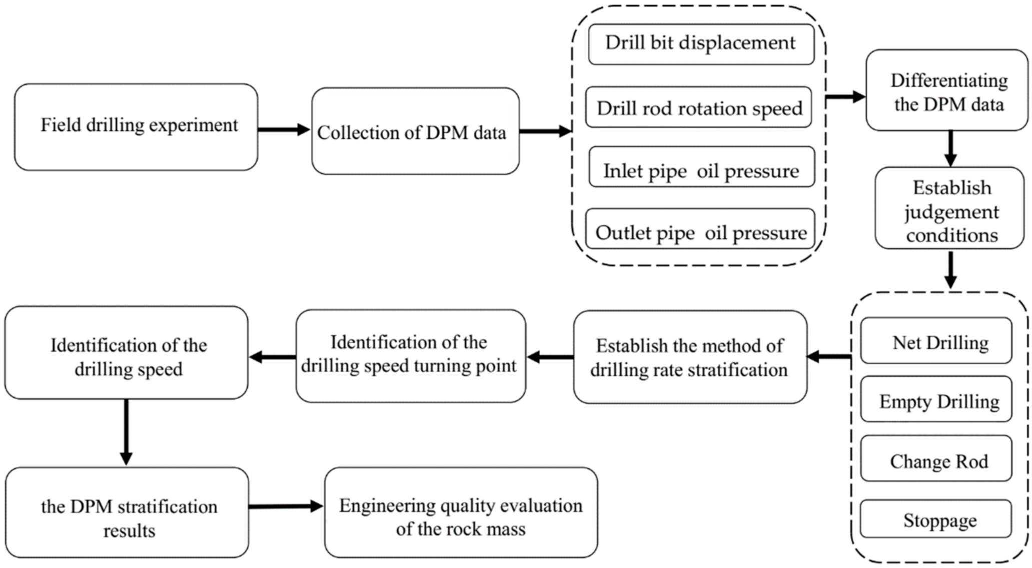

Figure 2. Flowchart of the DPM cataloguing method.

2.1. Field Drilling Experiment

The test site was located in Baota district, Yan'an city, Shaanxi Province (Figure 3). The test site mainly hosts Mesozoic-Cenozoic strata, including Triassic, Jurassic, Neogene and Quaternary strata. Among them, Quaternary loess is the most widely distributed, and the remaining strata are mostly scattered along the two sides of the valley. The rock lithology of the test site mainly includes sandstone and mudstone.

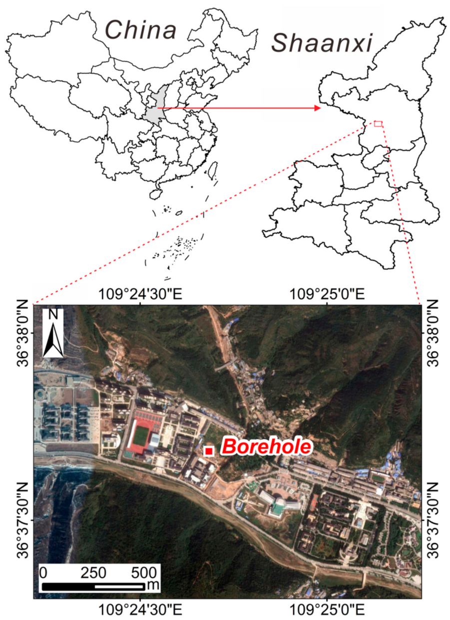

Figure 3. The test site of DPM application in Yan'an city, Shaanxi Province, China.

The test time was from 8–11 September 2018, a total of 4 days. Drilling was performed for approximately 12 h a day, and the total drilling depth was 102 m. The DPM system monitored and collected the drill bit displacement, drill rod rotation speed and oil pressure of the inlet and outlet pipes throughout the drilling process. At the same time, the testers carried out the coring operation and manual cataloguing and recorded the drilling depth by measuring the length of the drill pipe and the length of the residual rule each time. Through related programs, data analysis was performed on the collected rock-breaking response information of the drilling rig, and the rock-breaking response information of the drilling rig in the net drilling process was obtained.

Due to the complex and variable shapes of drilling rigs, a DPM system needs to be installed according to the shape of the considered drilling rig. The following is an explanation of the drilling rig at the test site of this paper. When installing the displacement sensor, it is necessary to fix the sensor on the drill chuck so that the sensor can move up and down with the drill chuck. The small ring is fixed at the end of the wire rope on the metal cylinder at the bottom of the drill to ensure that the wire rope is parallel to the movement direction of the drill chuck. When fixing the displacement sensor, a metal bracket can be made to fix it onto one side of the drill chuck. The maximum sensing distance of the speed sensor is generally 10~20 mm. During installation, an iron nail can be fixed onto the chuck of the drilling rig so that the iron nail rotates with the chuck. It should be ensured that the shortest distance between the iron nail and the speed sensor when it rotates with the chuck is less than the maximum monitoring distance of the speed sensor. When installing the oil pipe oil pressure sensor, the nut connecting the oil cylinder and the oil pipe is unscrewed, and a three-way pipe is used for connection. The three channels of the three-way pipe can be connected to the oil pipe and the sensor.

In this test, the collection frequency of the data logger is 1 s; that is, the DPM system monitors and collects the drilling rig's rock-breaking response information every second. In this test, the DPM system installed on the drilling rig was used for monitoring purposes during the drilling process. The sensors used in the test included a rope displacement sensor, a speed sensor, an oil inlet pipe oil pressure sensor, and an oil outlet pipe oil pressure sensor. The sensors were installed on the drilling rig, and the electrical signals were transmitted to the data logger through electric wires and displayed in real time (Figure 4). The parameters of the drilling rig and DPM system are shown in Table 1.

Figure 4. DPM sensors non-destructively installed on the drilling rig: (**a**) displacement sensor (**b**) rotation sensor (**c**) oil inlet pipe oil pressure sensor (**d**) oil outlet pipe oil pressure sensor (**e**) data acquisition system.

Table 1. The instrument used in the drilling test in Yan'an city.

Instrument Name	Model and Manufacturer	Characteristic	Range (Unit)	Description
Drilling Rig	DPP100-4HDQ from East Cocnor Commercial Vehicle Manufacturing System (Shiyan) Co., Ltd. of Shiyan city, China	Hydraulic rotary percussive	\	Diamond drill bit; measured accurately every time rods are added.
Displacement Sensor (Figure 4a)	DP-2000F from Tokyo Measuring Instruments Lab. of Tokyo, Japan	Installed onto the side of the take-off and landing system of the drilling rig to monitor the movement process of the drill bit and calculate the footage	2000 (mm)	For the rope displacement sensor, the rope end needs to be fixed, and the rope should be parallel to the direction of the drill rods.
Rotation Sensor (Figure 4b)	NBB10-30GM50-E0-V1 from Pepperl & Fuchs. of Mansham, Germany	Installed onto the side of the chuck of the drilling rig to monitor the change in the drill rod speed over time	1 (r/s)	During installation, the nail can be fixed onto the chuck of the drilling rig to make the nail rotate with the chuck; the shortest distance between the nail and the speed sensor should be less than 20 mm when the nail rotates with the chuck.
Oil Inlet and Outlet Pipes Oil Pressure Sensors (Figure 4c,d)	RS pressure inverter IND series from RS Components. of London, UK	Installed onto the oil supply pipes of the drilling rig to monitor the oil pressure of the drilling rig under different conditions	25 (MPa)	The tee pipe can be used for connection during installation; the size of the tee pipe depends on the shape of the oil pipes of the drilling rig.
Data Acquisition System (Figure 4e)	DataTaker DT80g from Saimo Flying Shier Technology Australia Company of Melbourne, Australia	Receives the electrical pulse signal output by the sensor, stores it in the memory of the data logger, and sends it to a compute	1 (Hz)	Keeps the battery of the data logger full.

2.2. DPM Data Collection

The DPM system recorded the different processes of drilling in real time including empty drilling, net drilling change rod and stoppage, and collected the bit displacement recorded by the displacement sensor, the drill pipe speed recorded by the rotational speed sensor, and the oil pressure recorded by the oil inlet and outlet pipe oil pressure sensors. The collected data were displayed by and processed by the data collector.

The data collection was mainly transferred between the U disk and the data collector. First, the U disk is inserted into the USB interface of the data collector, the data collector is disconnected from each sensor through the menu item on the data collector, and then the collected data are copied. After the data are copied, the connection between the collector and the U disk is closed. At this time, only the DBD file in the U disk must be copied to the computer. On the computer, the DBD file is converted into a CSV format file through DeView software, and finally, the CSV file is saved in XLSX format for subsequent data processing and other tasks.

2.3. Analysis of the Net Drilling Process and Drilling Speed Zones

A complete drilling process can be divided into net drilling and auxiliary processes. In the net drilling process, the drill bit touches the rock mass at the bottom of the borehole and rotates to break the rock, and the operating state of the drilling rig is drilling. In the auxiliary processes, the drill bit does not drill into the new rock mass at the bottom of the hole, including operations such as hollow drilling, adding drill rods, removing drill rods, and stoppage [19]. Among them, the net drilling process is an effective drilling process. By analyzing the data of the net drilling process, the variation in the drilling speed in sections along the depth direction can be obtained.

2.3.1. Differentiating the DPM Data

According to the collected response information of the drilling rig, the drilling rig's rock-breaking response information of the net drilling process was extracted. The net drilling process was judged according to the displacement, the rotation, and the oil pressures of the inlet and outlet pipes. Table 2 lists the judgement conditions for the net drilling process.

Table 2. Judgement conditions of the monitoring data for different drilling processes.

Rig Operating Status	Displacement Sensor (D)	Rotation Sensor (R)	Oil Pressure Sensor (P)
Empty Drilling	$D1 - D2 > a$	$R > 0$	Down Drill Rod: $P1 > P2$ Upper Drill Rod: $P1 < P2$
Net Drilling	$b < D1 - D2 < a$	$R > 0$	$P1 > P2$
Change Rod (adding or removing rods)	$D2 - D1 = 0$	$R = 0$	$P1 < P2$
Stoppage	$D2 - D1 = 0$	$R = 0$	$P1 = P2 = 0$

Note: D1 and D2 are the displacement lengths of the rope two seconds before and after the displacement sensor passes. R is the drill rod rotation speed. P1 is the oil pressure of the inlet pipe, and P2 is the oil pressure of the outlet pipe. The values of a and b are determined according to the law of monitoring data, where a represents the critical speed of drilling and hollow drilling in a certain rock formation, and b is the monitoring speed error in a certain rock formation. Different rock formations have different drilling resistances, so the values of a and b will also change. In this test, the values of a and b are 10 mm and 0 mm, respectively.

2.3.2. Identification of the Drilling Speed Turning Point

According to the monitoring data judgement criteria of different drilling processes in Table 2, the DPM data of the net drilling process of the drilling can be obtained. As shown in Equation (1), the accumulation of bit displacement during net drilling is expressed as a function of bit depth versus net drilling time.

$$Bit_{depth}(t_j) = Bit_{depth}(t_{j-1}) + Bit_{depth}\left(\Delta t_{pre-assigned}\right) \quad (1)$$

where Bit_{depth} is the drill bit depth, t_j and t_{j-1} are the times before and after sampling in the net drilling process and $\Delta t_{pre\text{-}assigned}$ is the time sampling frequency of the DPM system.

Therefore, it is necessary to determine the variation in the drill bit depth with net drilling time before determining the rate of penetration. In the DPM test, the drilling depth–time curve is approximately composed of several piecewise linear segments.

For the turning point of the drilling speed between each subarea, the correlation coefficients of each group are calculated by iterative calculation and the turning point is determined by comparison.

In the drilling depth–time curve, as long as the turning point of each subsection is determined, the drilling speed of each subsection can be calculated. The drilling speed is linearly fitted according to the data between each adjacent turning point. It is obtained by fitting the slope in the formula. It is clear that the correlation coefficients within each drilling speed partition are very close to unity. The slopes in the two adjacent intervals are different, which means that when the data after the turning point are included in the fitting of the previous drilling speed partition, the degree of correlation will be significantly reduced.

If the drilling data are smooth, that is, there is no jitter, since the time acquisition frequency is 1 s, the depth difference between every two points is used to determine the drilling speed. At this time, it is only necessary to identify the drilling speed change point.

However, in practice, drilling data are not completely smooth, so the turning point is not determined by only the sudden change in the rate of penetration calculated between every two points.

According to the different degrees of smoothness of the data, the total amount of data recorded is *n*, and m data are selected to fit and calculate the correlation coefficient. For example, the correlation coefficient from the 1st point to the m_{th} point is R_1, the correlation coefficient from the second point to the $(m + 1)_{th}$ point is R_2, the correlation coefficient of the third point to the $(m + 2)_{th}$ point is R_3..., and the coefficient of the $(n - m + 1)_{th}$ point to the n_{th} point is R_{n-m+1}. Then, we calculate the difference between the correlation coefficients before and after the control. If the difference is greater than a certain threshold value, the last point of the latter group is considered the turning point, that is, the $(j + m)_{th}$ point is the turning point, as shown in Equation (2).

$$\left|R_j - R_{j+1}\right| > \alpha \tag{2}$$

where $j \leq n - m$; α is the maximum critical value of the change in the correlation coefficient between the two groups of data before and after the control. Depending on the degree of smoothness of the data while drilling and the requirements for the degree of partitioning, m and α will change accordingly. In the experiment in this paper, according to the actual net drilling process data collected while drilling, the m value is 100, and α is 0.01.

2.3.3. Identification of the Drilling Speed

For each linear segment of the drilling depth–time curve, its constant velocity is determined using the classical least squares method.

The method of determining the constant rate of penetration and its corresponding depth interval can be expressed by Equations (3) and (4).

$$H(t + \Delta t) = k\Delta t + H(t) \tag{3}$$

$$k = \frac{H(t + \Delta t) - H(t)}{\Delta t} \tag{4}$$

where *H* represents the drilling depth corresponding to time *t* and *k* is the constant slope of a linear segment on the drilling depth–time curve, which is equal to the drilling speed on the linear segment.

For a linear segment on the drilling depth–time curve, we can control the relationship between the drilling depth H_j and the corresponding net drilling time t_j through sets of data, where the subscripts $j = l, l + 1... L$ $(1 \leq l < L \leq N)$ and N represent the last sampling time when drilling is completed. When there is a linear relationship between H_j and t_j, it can be described by the following Equation:

$$H(t) = kt + b \tag{5}$$

where *k* is the constant slope gradient of the linear segment in the drilling depth–time curve, and *b* is the constant coefficient. Using the least squares method, these two coefficients minimize the square of the total difference:

$$\sum_{i=1}^{L}\left[H(t_j) - \hat{H}(t_j)\right]^2 = \sum_{i=1}^{L}\left[H(t_j) - (kt_j + b)\right]^2 = Minimum \tag{6}$$

The constant coefficients *k* and *b* are determined by the following Equations:

$$k = \frac{\sum_{j=1}^{L}(t_j - \bar{t})(H(t_j) - \overline{H}(t_j))}{\sum_{j=1}^{L}(t_j - \bar{t})^2} \tag{7}$$

$$b = \overline{H}(t) - k\bar{t} \tag{8}$$

where $\bar{t} = \frac{\sum_{j=1}^{L} t_j}{L-l+1}$, $\overline{H}(t) = \frac{\sum_{j=1}^{L} H(t_j)}{L-l+1}$.

In addition, the regression index that determines the linear goodness of fit between the two is given by:

$$R^2 = 1 - \frac{RSS}{TSS} = 1 - \frac{\sum_{j=1}^{L} \left(H(t_j) - \hat{H}(t_j)\right)^2}{\sum_{j=1}^{L} \left(H(t_j) - \overline{H}(t_j)\right)^2} \tag{9}$$

where RSS is the residual sum of squares and TSS is the total sum of squares.

It can be seen from the above formula that the constant coefficient k can be regarded as the drilling speed of the section between time intervals t_1 and t_l. The closer the regression index R^2 is to 1, the better the linear correlation of the drilling speed.

3. Results and Analysis

3.1. Original DPM Data at Site

The results of the data collector were output to the computer, and the daily rock-breaking response information of the drilling rig was analyzed. Figures 5–8 show the change curve of the drill bit displacement, drill pipe speed and oil pressures in the inlet and outlet pipes with the drilling time during the whole process of DPM monitoring. Both the letters and numbers in Figures 5–8 indicate that drilling is not working.

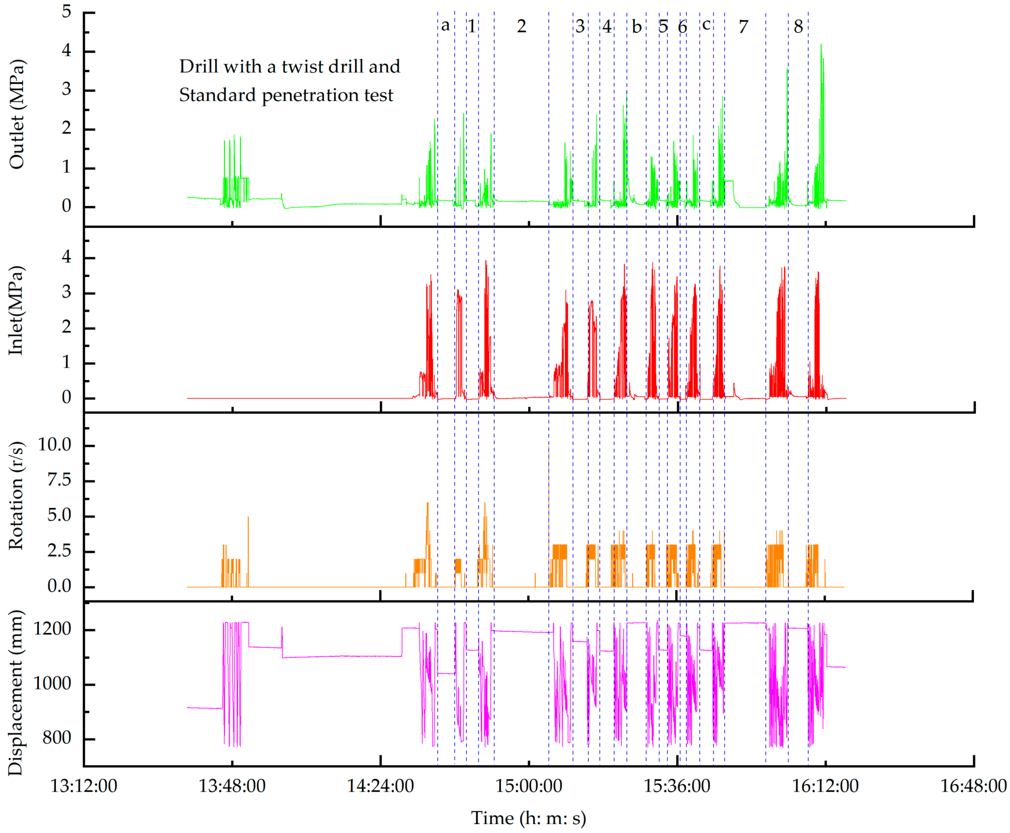

Figure 5. Rock-breaking response information–drilling time curves of a drilling rig drilling in Yan'an city on 8 September 2018 (drilling depth: 0.00–10.20 m. Outlet means oil pressure of outlet pipe, Inlet means oil pressure of inlet pipe, Rotation means drill rod rotation speed, Displacement means drill bit displacement, same as below).

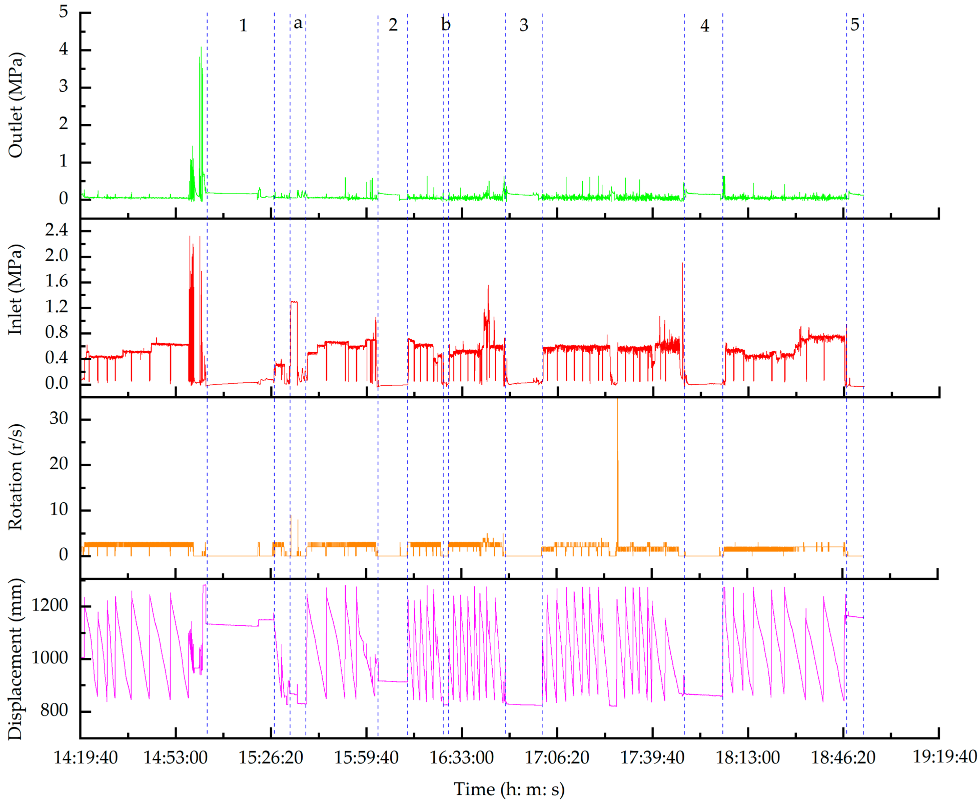

Figure 6. Rock-breaking response information–drilling time curves of a drilling rig drilling in Yan'an city on 9 September 2018 (drilling depth: 10.20–29.34 m).

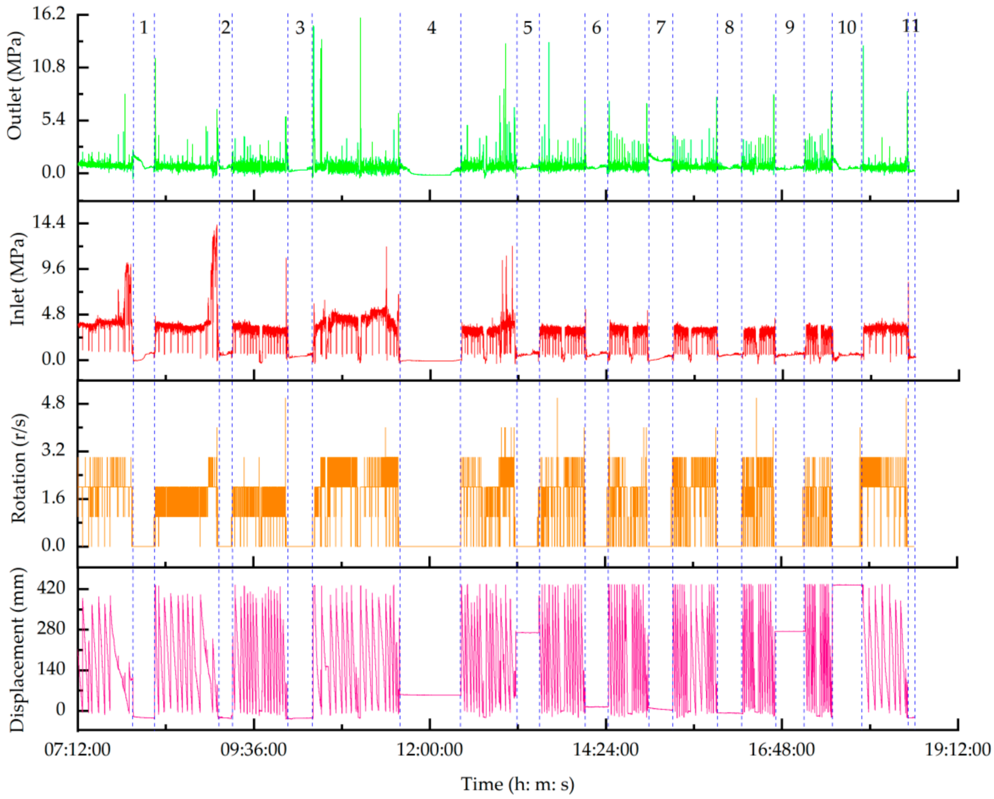

Figure 7. Rock-breaking response information–drilling time curves of a drilling rig drilling in Yan'an city on 10 September 2018 (drilling depth: 29.34–87.01 m).

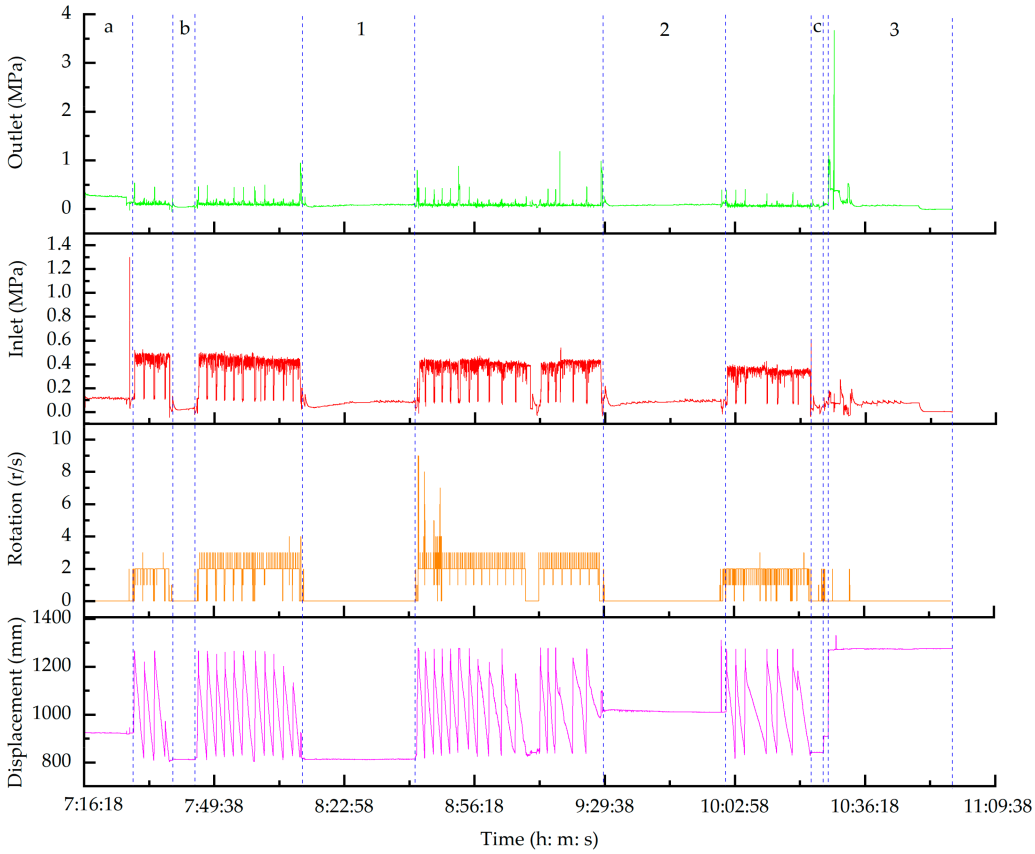

Figure 8. Rock-breaking response information–drilling time curves of a drilling rig drilling in Yan'an city on 11 September 2018 (drilling depth: 87.01–102.27 m).

The letters *a*, *b*, and *c* represent the stopped drilling state, in which case the drilling rig is generally being repaired, the drill is empty, or the rod addition operation is being performed.

The numbers 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11 represent the stopped drilling state when the rod extraction is being performed. After each coring is completed, the rod change (i.e., addition or removal) is performed. That is, except for when the drilling rig is in the shutdown state, the drilling rig is in the drilling state.

3.2. DPM Cataloguing-While-Drilling Results

According to the data processing methods described in Table 2, the time series-based drilling depth of the net drilling process is obtained. Figure 9 shows the drilling depth–time curve of the borehole in Yan'an city. The *y*-axis drilling depth in the picture is measured by a displacement sensor with an accuracy of 1 mm. The drilling depth is obtained by accumulating the displacement difference measured by the displacement sensor per second under net drilling, and the drilling depth per second under net drilling is obtained from the judgment conditions in Table 2. The drilling depth–time curve shows a piecewise linear change, and the slope of each linear section is the penetration rate within that section of depth. The drilling can be partitioned according to the penetration rate.

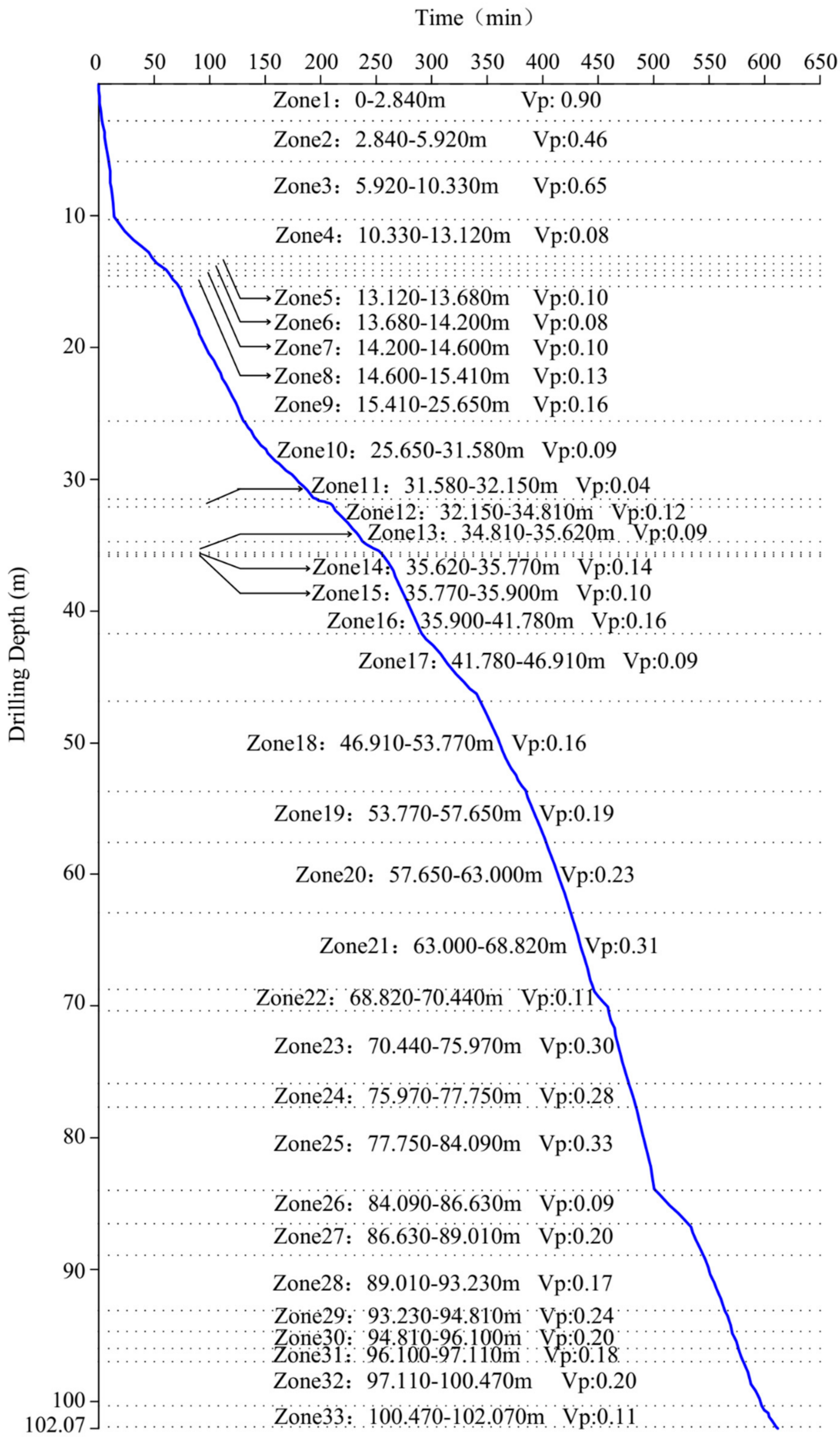

Figure 9. Drilling depth–time curve of the borehole in Yan'an city based on DPM cataloguing. V_P is the penetration rate, unit: m/min.

Using Equations (2)–(9), the drilling speed and regression index in the four drilling speed zones of the Yan'an borehole were calculated, and the results are shown in Figure 10. The results show that there is a very high linear correlation between the drilling depth H in each partition and the corresponding time t, and the confidence interval of the linear correlation is greater than 99%.

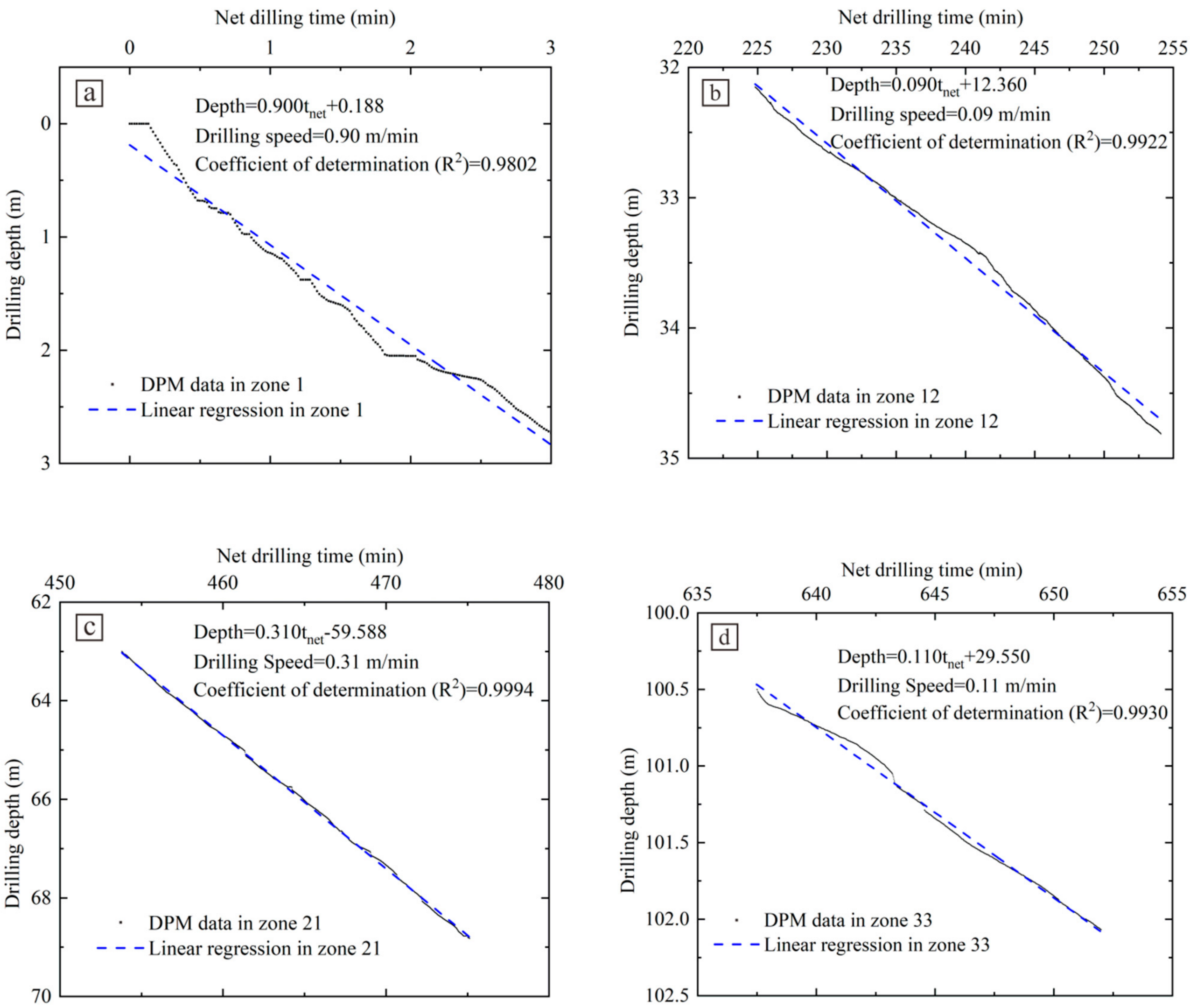

Figure 10. (**a**–**d**) Linear regression results of drilling depth and drilling time in some subzones of the borehole in Yan'an city.

The drilling depth shown in Figure 9 is divided into 33 zones by identifying the drilling speed, and the right half of Figure 11 shows the depth of each zone and the corresponding penetration rate. Therefore, to perform drilling rate stratification of the underground rock and soil mass, the DPM drilling depth–time curve can be recorded as the result for DPM cataloguing.

The left half of Figure 11 is the result of manual cataloguing of the borehole. It can be seen that the manual cataloguing divides the borehole into 21 depth intervals by identifying lithology. Figure 11 shows the comparison results of the two cataloguing methods with the drilling depth. The results show that the numbers of cataloguing partitions are different but that the depths of some partition interfaces are very close.

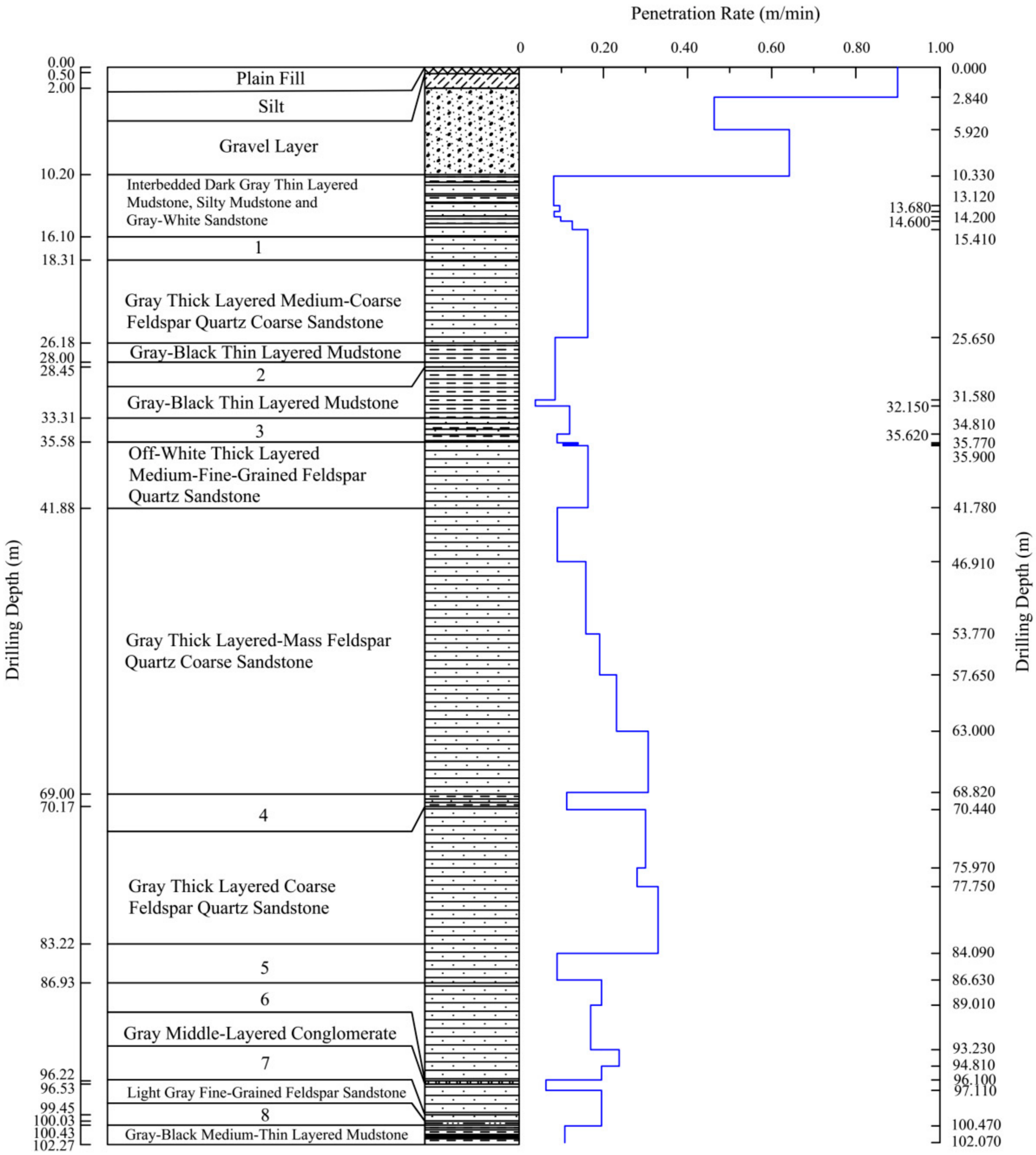

Figure 11. Contrast chart between manual cataloguing and DPM cataloguing of the borehole in Yan'an city. The numbers 1–8 refer to lithologies obtained by manual cataloguing. 1: Moderately thick layers of off-white fine-grained feldspar sandstone, 2: moderately thick layers of light grey fine-grained feldspar sandstone, 3: interbedded grey–white sandstone and grey–black mudstone, 4: grey–black mudstone with grey–white fine sandstone, 5: thick layers of off-white medium- to coarse-grained sandstone, 6: thick layers of grey coarse-grained feldspar/quartz sandstone, 7: thick layers of grey coarse feldspar/quartz sandstone, 8: dark grey argillaceous siltstone with fine sandstone interlayers.

4. Discussion

4.1. The Advantages of DPM in Borehole Cataloguing

Traditional manual cataloguing has the characteristic of being greatly affected by human error, ignoring the engineering quality of rock masses, and having low measurement accuracy. Through the DPM system installed in a drilling rig in Yan'an city for a cataloguing-while-drilling test, the automated results are compared with manual cataloguing results: the results are shown in Table 3, where u_i and v_i represent the interface depth values obtained by manual cataloguing and DPM cataloguing, respectively, and the rate of change in the interface depth values is obtained by the formula $(u_i - v_i)/u_i \times 100\%$. It is believed that DPM cataloguing has the following two advantages:

Table 3. Interface depth and zoning comparisons of DPM cataloguing and manual cataloguing for a borehole in Yan'an city.

Depth Range/m (DPM)	Depth Range/m (Manual)	Number of Zones (DPM)	Number of Zones (Manual)	Interface Value v_i/m (DPM)	Interface Value u_i/m (Manual)	$x_i = u_i - v_i$/m	(x_i/u_i)/%
0.000–10.330	0.00–10.20	3	3	10.33	10.2	−0.13	−1.27
10.330–15.410	10.20–16.10	5	1	15.41	16.10	0.69	4.29
15.410–25.650	16.10–26.18	1	2	25.65	26.18	0.53	2.02
25.650–35.900	26.18–35.58	6	4	35.90	35.58	−0.32	−0.90
35.900–41.780	35.58–41.88	1	1	41.78	41.88	0.10	0.24
41.780–68.820	41.88–69.00	5	1	68.82	69.00	0.18	0.26
68.820–70.440	69.00–70.17	1	1	70.44	70.17	−0.27	−0.38
70.440–84.090	70.17–83.22	3	1	84.09	83.22	−0.87	−1.05
84.090–86.630	83.22–86.93	1	1	86.63	86.93	0.30	0.35
86.630–96.100	86.93–96.22	4	1	96.10	96.22	0.12	0.12
96.100–97.110	96.22–96.53	1	1	97.11	96.53	−0.58	−0.60
97.110–100.470	96.53–100.43	1	3	100.47	100.43	−0.04	−0.04
100.470–102.070	100.43–102.27	1	1	102.07	102.47	0.40	0.39

(1) DPM cataloguing has the advantage of quality evaluation of rock mass engineering. At a layer interface depth, the percentage differences in the interface depth values obtained by DPM cataloguing and manual cataloguing are consistent. Since each constant drilling rate segment represents the same engineering conditions [21,35], DPM cataloguing can identify the depth of the layer interfaces of the borehole. In terms of the number of zones, manual cataloguing obtained 21 zones by identifying lithology, and DPM cataloguing obtained 33 zones by identifying the segmental slope of the drilling depth–time curve. For rock masses of the same lithology, the engineering properties may be different, which will cause DPM to record multiple drilling rate stratifications. This may be due to the variability in the internal structure of the rock mass and the unknown geological environment, leading to differences in the engineering properties. Similarly, even if two or more different rock formations are manually catalogued, but the penetration rate is the same, they can be regarded as the same type of rock formation in terms of engineering conditions. Identifying engineering geological rock groups is important in the research of rock mass engineering geomechanics. The correct division of engineering rock groups is conducive to the evaluation, analysis and understanding of underground rock masses [36]. Therefore, DPM can be used to effectively divide engineering geological rock groups. Notably, manual cataloguing is stratified by identifying lithology, and DPM cataloguing is stratified by identifying drilling velocity (engineering rock mass quality). Therefore, the DPM cataloguing cannot accurately give the lithological distribution of the underground rock mass. In the future application of the DPM cataloguing method, the results of manual cataloguing can be combined to achieve a more comprehensive evaluation of rock mass quality.

(2) The DPM system is mounted onto the drilling rig, which can monitor and collect the rock-breaking response information of the drilling rig in all underground rock and soil bodies in real time, to perform a rock mass engineering quality evaluation. The existing engineering quality evaluation methods can be divided into direct and indirect measurement methods [35]. Indirect measurement methods, such as the BQ method, require laboratory tests on recovered cores to measure their uniaxial compressive strength, longitudinal wave velocity, etc. Indirect measurement methods have

problems such as high costs, long durations, and high difficulty. Direct measurement methods (such as standard penetration, static and dynamic penetration methods) are mainly used for softer soils, not for harder and more complex rock masses. The use of the DPM method to evaluate the quality of rock mass engineering solves the defects of the above methods. It has the advantages of low cost, short duration, and low difficulty and can be used to evaluate the quality of rock mass engineering in any rock masses. In addition, relevant programs can be added to the data logger to display real-time changes in the penetration rate with increasing drilling depth so that the engineering quality of the underground rock mass can be evaluated without coring. In addition, relevant programs can be added to the data collector to display the change in the drilling speed with the drilling depth in real time. Many scholars have found that the rock-breaking response information of the drilling rig, such as the drilling speed, is highly correlated with some physical and mechanical parameters, such as drilling-specific work [33], rock uniaxial compressive strength [37,38], rock mass block index (RBI) [39], and rock quality designation (RQD) [40]. Thus, when studying a specific underground physical and mechanical parameter in a certain area, it is necessary to collect and analyze only the rock-breaking response information of the drilling rig, so the engineering quality of the underground rock mass can be evaluated in real time without coring.

4.2. The Scientific Validity of DPM Cataloguing in Adapting Engineering Management

At present, there are problems in drilling engineering, such as the variability in drilling personnel quality, complicated drilling production management processes, difficult construction quality management, and low drilling quality. Compared with manual cataloguing, DPM cataloguing has the following two advantages:

(1) DPM cataloguing simplifies drilling production management processes. The DPM system can collect the rock-breaking response information of the drilling rig throughout the drilling process, and the information collected can record the drilling speed, drill pipe rotation speed, tubing oil pressure and other information, which will help guide the follow-up engineering of the site. According to this information and the judgement basis in Table 2, the operating state of the drilling rig can also be quickly judged, and the change in information while drilling and in the nondrilling state and its duration can be directly obtained, which can effectively prevent rig workers from neglecting their work. In addition, if a GPS locator is installed before drilling [41], the position and drilling depth information of the drilling rig can also be obtained in real time.

(2) DPM cataloguing can eliminate the problem of the falsification of drilling engineering catalogue data. During field drilling, rig workers often catalogue false data for two reasons. One is that some core sections with a high sampling rate are scattered and misplaced due to the rush of the construction period, resulting in the core depth not corresponding to the in situ depth. The second is that the core lithology does not correspond to the original stratum due to the low sampling rate of some core sections, and different cores from other places may be placed incorrectly. Therefore, we can apply this result to the management of on-site drilling engineering and determine the actual drilling depth corresponding to the core according to the results catalogued by DPM to achieve accurate sampling depths for all cores.

5. Conclusions

In this paper, a novel borehole cataloguing method based on a DPM system is proposed. This method can distinguish the engineering conditions of underground rock and soil while supervising the whole process of drilling to improve drilling engineering management. DPM fills the gap in the application of geologic cataloguing technology while drilling. This work includes three steps: field drilling experimentation, collection of DPM data, analysis of both the net drilling process and the drilling speed zone. In this paper, the

DPM borehole-cataloguing method is applied to the drilling process of a 102 m borehole in Yan'an city. The DPM system is used to monitor and collect the drill bit displacement, drill pipe rotational speed and inlet and outlet pipe oil pressures throughout the drilling process. By analyzing the above information, the drilling depth–time curve in the net drilling process and the drilling speed of each depth section are obtained. According to the comparative analysis of the results of the manual cataloguing of cores, the following borehole cataloguing method based on the DPM system is proposed:

(1) The interface depth values obtained by DPM are similar to the corresponding values obtained by manual cataloguing, and the percentage difference in the interface depth between the two ranges from −1.27% to 4.29%. The numbers of zones obtained by DPM cataloguing and manual cataloguing are different. According to the drilling depth–time curve, DPM cataloguing divides the borehole into 33 zones. By identifying lithology, manual cataloguing obtains 21 zones.
(2) When the rock mass is divided into engineering geological rock groups, the DPM cataloguing can not only identify the depths of the layer interfaces in the borehole but also accurately provide the stratification result of the rock mass engineering quality to realize the evaluation of rock mass engineering quality during the drilling process.
(3) With the help of the DPM system, the information of the whole drilling process and the rock-breaking response information of the drilling rig can be obtained. Using this information, the working statuses of hollow drilling, drilling, rod replacement, and shutdown throughout the drilling process can be obtained to effectively supervise the drilling process. The results of DPM cataloguing can also eliminate the problem of falsification of drilling engineering catalogue data and ensure the accuracy of core information.

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