DPM time management analysis for drilling a 200 m deep hole in ground investigation

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Abstract. This paper applies the drilling process monitoring (DPM) method to record and analyse the digital real-time data for the full process of the hydraulic rotary coring project along a 200 m deep drillhole. According to the DPM data, the whole drill project is divided into four periods. The working period (or the full drilling process) consists of a total of 88 roundtrips and costs a total of 76.71 hours. Each roundtrip can be classified into four sections: inserting, drilling, retrieving, and extracting processes. The time distribution of each individual process along the 200 m deep drillhole is obtained by DPM data. As the drillhole depth increases, the time of the total roundtrip, the inserting process, and the retrieving process for one roundtrip increases linearly. The ground strata, the drill machine condition, and the operators’ effectiveness determine the variations in the elapsed time of the drilling process. Furthermore, four types of malfunctions and associated time distribution can be identified by the abnormal DPM data. The factual data and results presented in the paper can quantitatively describe the time distribution of individual drilling processes and provide a digital field management method for drilling information.

Keywords: DPM; Drilling process monitoring; Hydraulic rotary drilling; Time distribution; Field data; Drill management

1. Introduction

1.1. General

Hydraulic rotary drilling is a commonly used and essential process for ground investigation [1]. For a typical hydraulic rotary drilling, the drill bit breaks the ground materials and advances into deeper geomaterials for filling the barrel with soil or rock cores in a cylindrical hole of about 100 mm diameter. Therefore, drilling itself contains mass data which can indicate the geomaterial properties, the conditions of drill machines, and the operations during the project [2-6].

Collection and utilization of drilling information data are important for the operation and management of the drilling project. Steven et al. [7] attempted to use the management of drilling information to improve the drilling efficiency. Li et al. [8] recorded the drilling parameters for the evaluation of the drilling risk. Chernyi [9] established the management system for drilling rigs. La [10] developed the information management system for the improvement of drilling and blasting in mining projects. However, the instrumented drilling techniques have not become a common ground investigation tool in drill projects [11]. Mass factual data of drilling process have not been collected and utilized.

Yue et al. [4, 5, 12] invented the drilling process monitor (DPM) technique and developed the real-time series method for data recording and analysis. The DPM can offer digital data in time sequence
and associated analysis method for ground characterization. Chen and Yue [13, 14] determined the weathering grades of drilled geomaterials by the DPM data. Li and Itakura [15] indicated that the DPM is helpful in identifying effective drilling process and improve the calculation precision. Li et al. [16, 17] applied DPM for the advanced geological prediction in tunnel construction. Feng et al. [18] used DPM for karst identification and grout evaluation of the Dehou reservoir in China. Wang et al. [19] studied the in-situ digital profiling of soil to rock strength by DPM data.

1.2. Objective of this paper

Reviewing previous studies about the utilization of drilling information, few applications were used for the quantitative descriptions on the time distribution of different processes and operations during the full drilling process. Such data can improve the quality of production and management. The in-situ decision making can be done based on the time distribution to direct the drill project in real-time.

In this paper, the DPM technique is used to record and analyze the drilling parameters in the project of Underground Space Survey in Xi’an city by China Geological Survey. In-situ digital drilling data is recorded and analyzed for accurately and quantitatively identifying the time distribution of each individual process and associated operations along the drillhole.

2. Full drilling process for hydraulic rotary coring drillhole

2.1. Hydraulic rotary drilling equipped with DPM on site

The drilling project aims to conduct the ground investigation and develop urban underground space in Xi’an city. The drillhole is located at the loess tableland between Xi’an city and Jingyang county with the coordinates 34.48°N, 108.85°E. The loess tableland is a problematic area with loose structure, which needs investigation and protection during the development of the underground space. The typical XY-2-type hydraulic rotary drilling machine and the polycrystalline diamond compact drill bit with 110 mm diameter are used for the drillhole. The total drillhole depth is 199.984 m. The geomaterials of the drilled strata are mainly loess and clay.

For recording and analyzing the digital drilling information during the full process in the project, the DPM can be easily and non-destructively mounted onto the hydraulic rotary drilling machine on site as shown in Fig. 1. It can automatically, objectively, and continuously record the rotation data, displacement data, and pressure data in real-time series. The data acquisition device can control the sampling of digital signals from the transducers. The time-sampling interval is 1 second in this case.

![Diagram of hydraulic rotary drilling machine equipped with DPM](image)

**Figure 1.** The hydraulic rotary drilling machine equipped with DPM on site

2.2. Time distribution of the whole drillhole project by DPM data

According to the original DPM data collected by the transducer in real time, a series of drilling parameters can be obtained, as shown in Fig. 2. Based on the drilling parameters, the quantitative
description of the in-situ strength profile and spatial distribution of the drilled geomaterials have been studied by Wang et al. [19]. Furthermore, the time distribution of different processes and operations can also be stated by DPM data in real-time sequence.

![Figure 2. Flow chart of DPM data for hydraulic rotary drilling project](image)

Each individual process during the drilling project has a specific type of DPM data. In general, the whole project can be divided into four periods, as shown in Table 1. For the working period (or full drilling process), the DPM data corresponds to several processes associated with different operations for completing the 200 m deep drillhole. The details of this process are discussed in the next section. The total working period in this case is 76.71 hours. For the breakdown maintenance period, the DPM data corresponding to the breakdown part is abnormal (e.g., out of range). The total duration of this period is 19.34 hours. During the field site disposal period, workers collect the core samples and handle the site related matters; the drill machine usually stays in the warm-up status with stable and low DPM data. The total duration of this period is 72.00 hours. At last, the elapsed time for the rest period is 365.95 hours.

### Table 1. Summary of the time distribution for the whole project of drilling the 200 deep drillhole

| Project period description                     | Elapsed time A (hour) | Percentage A | Elapsed time B (hour) | Percentage B |
|-----------------------------------------------|-----------------------|--------------|-----------------------|--------------|
| Working period                                | 76.71                 | 14.4%        | 76.71                 | 45.7%        |
| Breakdown maintenance period                  | 19.34                 | 3.6%         | 19.34                 | 11.5%        |
| Core samples and field site disposal          | 72.00                 | 13.5%        | 72.00                 | 42.8%        |
| Rest period                                   | 365.95                | 68.5%        | excluded              | 0.0%         |
| Total                                         | 534.00                | 100.0%       | 168.05                | 100.0%       |

### 2.3. Individual drilling operations associated with the full drilling process

The full hydraulic rotary drilling process is formed with a series of roundtrips [19]. A typical roundtrip consists of the following processes: inserting the bit-sampler down to the bottom of the drillhole; rotating the drill rods for stirring the mud slurry; drilling and filling the barrel with new ground materials; cutting the core samples for extraction; retrieving the filled barrel back to the ground; collecting the core samples from the barrel. During the drilling project, the roundtrip is repeated one by one for drilling deeper geomaterials until the target drill depth is reached. In this case, a total of 88 roundtrips were completed for the 200 m deep drillhole.

The original DPM data for the full drilling process of two successive roundtrips in the case (Nos. 58 and 59) are shown in Fig. 3. It contains the displacement data, rotation data, and pressure data in real-time sequence which can be used for identifying different processes.
Figure 3. DPM data for four sub-processes in two roundtrips Nos. 58 and 59 of 88 roundtrips associated with the 200 m deep drillhole.

Section I of one roundtrip contains the inserting bit-sampler down process. The chuck position data is greater than zero and unchanged, the rotation data is equal to zero, and the pressure data remains unchanged. The elapsed times of the roundtrip 58 and 59 are 1373 s and 1384 s, respectively.

Section II consists of the drilling process with three subordinate processes. Section II.1 includes the stirring drill rods and bit process for facilitating the drilling effect. The chuck position data changes slightly, the rotation data is greater than zero, and the pressure data is equal to zero. The elapsed times of the roundtrips 58 and 59 are 469 s and 250 s. Section II.2 consists of the net drilling process. It is the actual coring operation in which the drill bit breaks the geomaterials and advances into deeper geomaterials. The chuck position data changes down and up periodically, the rotation data is greater than zero, and the pressure data fluctuates within a narrow range. The elapsed times of roundtrip Nos. 58 and 59 are 687 s and 656 s, respectively. Section II.3 is the cutting core samples process; the machine handler increases the hydraulic pressure and speeds up the revolution to cut off the bottom of core samples for extraction. The elapsed times of roundtrip Nos. 58 and 59 are 374 s and 209 s, respectively.

Section III is the retrieving drill rods and bit process, the filled barrel and drill rods are retrieved back to the ground. The associated drilling parameters are similar to the data of inserting process. The elapsed times of roundtrip Nos. 58 and 59 are 1438 s and 1500 s, respectively.

Section IV is the extracting core samples process in which the cores are collected from the barrel on the ground. The related operations cause the chuck position data to fall to the lowest value initially and rise finally and the pressure data to fall to zero initially and rise finally. The elapsed times of roundtrip Nos. 58 and 59 are 233 s and 177 s, respectively.
The specific time period for each individual process of the two roundtrips is shown in Table 2. The total durations of roundtrip Nos. 58 and 59 are 4574 s and 4176 s, respectively.

**Table 2. Time distribution for the full drilling process of the two roundtrips**

| Roundtrip No. | Time period (hour: minute: second) | Individual process | Elapsed time (s) |
|---------------|-----------------------------------|--------------------|-----------------|
| No. 58        | 09:46:32AM - 10:09:25AM           | Inserting process  | 1373            |
|               | 10:09:25AM - 10:34:56AM          | Drilling process   | 1530            |
|               |                                   | Stirring           | 469             |
|               |                                   | Coring             | 687             |
|               |                                   | Core cutting       | 374             |
|               | 10:34:56AM - 10:58:55AM          | Retrieving process | 1438            |
|               | 10:58:55AM - 11:02:49AM          | Extracting process | 233             |
| No. 59        | 11:02:49AM - 11:25:54AM          | Inserting process  | 1384            |
|               | 11:25:54AM - 11:44:30AM          | Drilling process   | 1115            |
|               |                                   | Stirring           | 250             |
|               |                                   | Coring             | 656             |
|               |                                   | Core cutting       | 209             |
|               | 11:44:30AM - 12:09:31AM          | Retrieving process | 1500            |
|               | 12:09:31AM - 12:12:29AM          | Extracting process | 177             |

3. DPM analysis results for the time management along the drillhole

3.1. Time distribution of the full drilling process among a total of 88 roundtrips along the drillhole

Based on the analysis results of the individual process of the roundtrips as the two examples, the elapsed time of each roundtrip among a total of 88 roundtrips along the 200 m deep drillhole is shown in Fig. 4. It is evident that the elapsed time of each roundtrip increases as its depth increases, as shown in the following linear regression function.

\[
\text{Total elapsed time of one roundtrip} = 24.3 \times \text{Drillhole depth} + 295.8 \tag{1}
\]

Furthermore, the first seventeen roundtrips (Nos. 1 to 17) are the non-coring roundtrips so that the retrieving and extracting processes are equal to zero in these roundtrips. The four roundtrips (Nos. 20, 30, 37 and 53) are the malfunction roundtrips and the durations are longer than the normal roundtrips.

**Figure 4.** Time distribution of each roundtrip among a total of 88 roundtrips from ground surface to deep in the ground
Fig. 5 shows the time distribution of four individual processes during each roundtrip along the 200 m deep drillhole. It is evident that the elapsed times of the inserting and retrieving processes for each roundtrip almost linearly increase as the drillhole depth increases. They can be expressed as the following linear regression functions. Due to the first seventeen roundtrips (Nos. 1 to 17) are the non-coring roundtrips, the drillhole depth of these non-coring roundtrips are not included in the functions.

Total elapsed time of inserting process in one roundtrip = 10.9 × Drillhole depth − 17.0 \hspace{1cm} (2)

Total elapsed time of retrieving process in one roundtrip = 11.8 × Drillhole depth − 174.8 \hspace{1cm} (3)

The elapsed time for the extracting process of each roundtrip is almost constant or independent with respect to the drillhole depth, which corresponds to the average value and the standard deviation of 194 s and 28 s, respectively. The total elapsed times of the inserting, retrieving, drilling, and extracting processes are 85935 s, 82048 s, 45148 s, and 13786 s (37.9 %, 36.2 %, 19.9 %, and 6.0 %), respectively. The elapsed time for the total drilling process of each roundtrip has the average value and the standard deviation of 513 s and 339 s, respectively. The variations are due to the ground strata, the drill machine condition, and the operators’ effectiveness.

![Figure 5. Time distribution of four individual processes during each roundtrip along the 200 m deep drillhole](image)

3.2. Time distribution of the malfunctions during the whole project

The DPM data was used to analyse the time distribution of the typical malfunctions during the whole project. During the full drilling process of roundtrips, Figs. 5 and 6 show that the elapsed times of the four roundtrips (Nos. 20, 30, 37 and 53) are much longer than other roundtrips.

The jamming of rotary drilling rods occurred on the roundtrip No. 20 and the rotation data was equal to zero abnormally. The repair time was 0.27 hours. The drilling rods dropped down accidentally during the roundtrip Nos. 30 and 53 and the displacement data was out of the normal range. The repair times were 0.23 and 0.32 hours, respectively. The samples dropped out of the barrel accidentally during the roundtrip No. 37 and the DPM data showed consistent displacement data without retrieving and extracting process. The repair time was 0.51 hours.

During the field site disposal period mentioned above, the machine engine failure occurred three times and the pressure data was out of the normal range. The total repair time was 18.01 hours. The details are shown in Table. 3.
Table 3. Time distribution of the malfunctions and repair period along the 200 m deep drillhole

| Malfunction cases                      | Time of occurrence | Roundtrip No. | Elapsed time of repair (hour) | Diagnosis with DPM data                        |
|----------------------------------------|--------------------|---------------|-------------------------------|------------------------------------------------|
| Engine failure of drill machine        | Day 2 15:10PM      | N/A           | 6.33                          | Pressure data out of normal range              |
|                                        | Day 8 10:52AM      | N/A           | 5.18                          | Pressure data out of normal range              |
|                                        | Day 13 16:02PM     | N/A           | 6.50                          | Pressure data out of normal range              |
| Jamming of rotary drilling rods        | Day 3 10:13AM      | No. 20        | 0.27                          | Rotation data is equal to zero abnormally      |
| Drilling rods dropped down             | Day 5 11:13AM      | No. 30        | 0.23                          | Displacement data out of normal range          |
|                                        | Day 14 14:47PM     | No. 53        | 0.32                          | Displacement data out of normal range          |
| Samples dropped out                    | Day 7 11:08AM      | No. 37        | 0.51                          | Consistent displacement data without retrieving and extracting process |

4. Conclusions
The DPM logging has been presented for identifying the time distribution of individual process and associated operations of the hydraulic rotary core drilling project along a 200 m deep drillhole. The in-situ digital DPM data can record the full drilling process in real-time. The factual data and results can quantitatively describe the time distribution of different processes during the project and provide a digital field management method for drilling information.

The whole drill project can be divided into four periods as per the DPM data. They are working period (or the full drilling process), breakdown maintenance period, core samples, field site disposal period, and rest period. The elapsed time of each period is calculated by DPM data.

The full drilling process consists of one roundtrip after another. One roundtrip can be classified into four sections: inserting process, drilling process, retrieving process, and extracting process. Each process refers to specific operations with the corresponding DPM data. The details on the time distribution of each section are further analyzed by the data of two successive roundtrips. During the two successive roundtrips (Nos. 58 and 59), the inserting process lasts for 1373 s and 1384 s, the drilling process costs 1530 s and 1115 s, the retrieving process costs 1438 s and 1500 s, and the extracting process costs 233 s and 177 s.

According to the analysis results of the individual process, the elapsed times of each roundtrip among a total of 88 roundtrips along the 200 m deep drillhole are shown. The elapsed times of the total roundtrip, the inserting process, and the retrieving process almost linearly increase as the drillhole depth increases. The elapsed time of the extracting process is almost constant or independent with respect to the drillhole depth. The variations in the drilling process are determined by the ground strata, the drill machine condition, and the operators’ effectiveness.

For the whole drill project, four types of malfunctions with a total time of 19.34 hours occurred during roundtrips Nos. 20, 30, 37, and 53 with abnormal DPM data.

5. Reference
[1] Liu, G.Z., Zhou, Z.Z., Lin, Y.X. 1998. History of China drilling explorations. Beijing, China: Geology Publication House (in Chinese).
[2] Somerton, W.H. 1959. A laboratory study of rock breakage by rotary drilling. Trans AIME, 216:92-7.
[3] Detournay, E., Defourny, P. 1992. A phenomenological model for the drilling action of drag bits. *International Journal of Rock Mechanics and Mining Sciences*, 29(1), 13-23.

[4] Yue, Z.Q., Lee, C.F., Law, K.T., Tham, L.G., Sugawara, J. 2002. Use of HKU Drilling Process Monitor in slope stabilization, *Chinese Journal of Rock Mechanics and Engineering*, 21(11), 1685-1690.

[5] Yue, Z.Q., Lee, C.F., Law, K.T., Tham, L.G. 2004. Automatic monitoring of rotary-percussive drilling for ground characterization-illustrated by a case example in Hong Kong, *International Journal of Rock Mechanics and Mining Sciences*, 41, 573-612.

[6] Aarsnes, U.J., Acikmese, B., Ambrus, A. 2016. Robust controller design for automated kick handling in managed pressure drilling. *Journal of Process Control*, 47, 46-57.

[7] Steven, J.S., William, C.S., Glenn, R.M.2006. The management of drilling-engineering and well-services software as safety-critical systems. *SPE Drilling & Completion* 21, 141-147.

[8] Li, Q., Chang, D., Xu, Y.Z., Tang, J.P., Liang, H.J. 2009. Drilling risk management system based on knowledge integration. *Acta Petrolei Sinica*, 5.

[9] Chernyi, S.G. 2016. Improving performance of microprocessor network management platform for Ethernet systems drilling rigs. *Instruments and Systems: Monitoring, Control, and Diagnostics* 1, 2-10.

[10] La, R.D. 2020. The development of an information management system for the improvement of drilling and blasting in mining operations. *Computer Applications in the Mineral Industries*. 367-372.

[11] Rai, P., Schunesson, H., Lindqvist, P.A., Kumar, U. 2014. An overview on measurement-while-drilling technique and its scope in excavation industry. *Journal of the Institution of Engineers (India): Series D*, 96(1), 57-66.

[12] Yue, Z.Q. 2014. Drilling process monitoring for refining and upgrading rock mass quality classification methods, *Chinese Journal of Rock Mechanics and Engineering*, 33(10), 1977-1996 (in Chinese).

[13] Chen, J., Yue, Z.Q. 2015. Ground characterization using breaking-action-based zoning analysis of rotary-percussive instrumented drilling. *International Journal of Rock Mechanics and Mining Sciences*, 75, 33-43.

[14] Chen, J., Yue, Z.Q. 2016. Weak zone characterization using full drilling analysis of rotary-percussive instrumented drilling. *International Journal of Rock Mechanics and Mining Sciences*, 100(89), 227-234.

[15] Li, Z., Itakura, K.I., Ma, Y. 2014. Survey of measurement-while-drilling technology for small-diameter drilling machines. *Electronic Journal of Geotechnical Engineering*, 19(2), 10267-10282.

[16] Li, S., Xue, Y., Tian, H., Li, Z., Wang, Z., Qiu, D., Yang, W. 2016. Identifying the geological interface of the stratum of tunnel granite and classifying rock mass according to drilling energy theory. *Arabian Journal of Geosciences*, 9(1), 1-11.

[17] Li, S., Liu, B., Xu, X., Nie, L., Liu, Z., Song, J., Fan, K. 2017. An overview of ahead geological prospecting in tunneling. *Tunnelling and Underground Space Technology*, 63, 69-94.

[18] Feng, S.X., Zhao, Y.F., Wang, Y.J., Wang, S.Y., Cao, R.L. 2020. A comprehensive approach to karst identification and groutability evaluation – A case study of the Dehou reservoir, SW China. *Engineering Geology*, 269, 105529.

[19] Wang, X.F., Zhang, M.S., Yue, Z.Q. 2021. In-situ digital profiling of soil to rock strength from drilling process monitoring of 200 m deep drillhole in loess ground. *International Journal of Rock Mechanics and Mining Sciences*, 142:104739.

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