Monitoring of Drill System Behavior for Water-Powered In-The-Hole (ITH) Drilling

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Abstract: A detailed understanding of the drilling system and the drilling control is required to correctly interpret rock mass conditions based on monitored drilling data. This paper analyses data from hydraulic in-the-hole (ITH) drills used in LKAB's Malmberget mine in Sweden. Drill parameters, including penetration rate, percussive pressure, feed pressure, and rotation pressure, are monitored in underground production holes. Calculated parameters, penetration rate variability, rotation pressure variability, and fracturing are included in the analysis to improve the opportunity to predict rock mass conditions. Principal component analysis (PCA) is used to address non-linearity and variable interactions. The results show that the data contain pronounced hole length-dependent trends, both linear and step-wise linear, for most parameters. It is also suggested that monitoring can be an efficient way to optimize target values for drill parameters, as demonstrated for feed force. Finally, principal component analysis can be used to transfer a number of drill parameters into single components with a more straightforward geomechanical meaning.

1. Introduction

Over recent decades, drill monitoring, or measurement while drilling (MWD), has become a well-established technique to characterize the penetrated rock mass in the mining and petroleum industries [1]. The technique can be used for drilling in different types of rock, it does not cause any disturbances in production, and it provides high-resolution information on the rock mass in an inexpensive way. It has been used for several drilling techniques, including rotary drilling, percussive drilling, and core drilling [2–17]. However, despite the potential of the technique, it has not yet become an independent tool to support decision-making in underground mine operations.

One identified remaining problem with the drill monitoring technique is the analysis of raw monitoring data. In percussive drilling, the most important monitored drill parameters are penetration rate, percussive pressure, feed pressure, and rotation pressure. Variations in these parameters along the length of the hole, is the result from the combined effect of variations in the properties of the penetrated rock mass, drill operators, and drill control systems [6,14]. With variations in the rock mass, parameter settings must be adjusted to improve drilling. Advanced control systems on modern drill rigs will always adjust drill parameters independently to avoid drilling problems and damage to the drill string and machine [6,14,18].

Another challenge for analysis is that monitored drill parameters are not independent, but highly correlated [14]. For example, high penetration rate can be recorded not only due to soft or fractured rock, but also due to high (optimal) feed pressure. Comparatively low penetration rates can be caused by low feed pressure and/or inadequate air pressure or by hard rock. Thus, any single recorded parameter cannot independently describe the characteristics of the rock mass in a conclusive way.

A descriptive drilling response is increased signal variability, particularly for rotation pressure and penetration rates when fractured or inhomogeneous rock is encountered. The increased variability of the rotation pressure is caused by alternating bit jamming effects and the sudden release of the bit when the rotation resistance is overcome. Meanwhile, variability in the penetration rate can be explained by small openings in the rock mass causing increasing forward speed of the drill string, interrupted by a sudden stop when solid rock is encountered again. Many researchers have noticed this behavior, e.g., [5,19,20].

A parameter called fracturing has been suggested by [21] as an indicator of rock mass inhomogeneity; the parameter can be calculated by combining the variability of the penetration rate and the variability of the rotation pressure. This has been improved more recently by [22].

A detailed understanding of the drilling system and the drilling control is required to correctly interpret the rock mass conditions based on monitored drilling data. This paper examines the drilling response for a production drill rig, drilling fan-shaped, upwards holes with hydraulic in-the-hole (ITH) hammers. The analysis suggests a better rock mass model can be developed by understanding and eliminating the variations caused by the external influence of operators and drill control systems.

2. Methodologies

The research described in this paper is mainly based on a literature review and the collection and analysis of drill monitoring data. Figure 1 presents the research methodologies followed in this study. An extensive literature review has been performed, including related previous research published in peer-reviewed journals, conference proceedings, research and technical reports, PhD theses, etc.
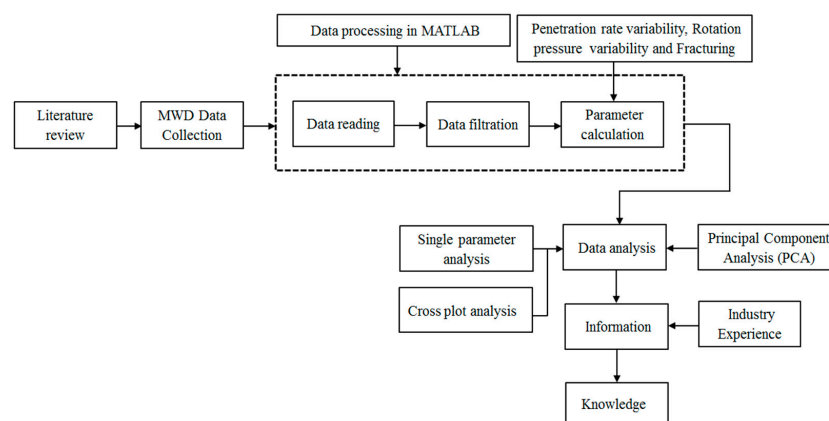

Figure 1. Research methodologies.

MWD data (saved in XML IREDES compact file format) are collected from six automated drill rigs of the same type. Two types of IREDES files are used: 'Data Quality (DQ)' files that contain coordinates of the collar and the bottom of the hole and 'MWD (MW)' files that include the depth, time, feed pressure, rotation pressure, percussive pressure, and penetration rate for each borehole. After data collection, the data have been filtered using MATLAB (The MathWorks, Inc., Natick, MA, USA). The raw data needs to be filtered since it contains some incorrect or faulty values. For example, the maximum value of the monitored penetration rate is +1184.462 m/min and the minimum value is −16.114 m/min. This maximum value is unrealistic, as the bit cannot move at this speed, even in open air, and the negative value of the penetration rate is simply not possible since the used measurement system only records forward movements. Both of these values are clearly faulty and need to be removed from the raw dataset. In addition, zero values of any monitored data are incorrect and are considered measurement errors in this study. The applied filter limits are: for the penetration rate, 0.1 and 4 m/min; for the percussive pressure, 5 and 200 bars; for the feed pressure, 35 and 100 bars; and for the rotation pressure, 25 to 125. After data collection and filtration, data has been further

processed and different parameters, such as penetration rate variability, rotation pressure variability, and fracturing, based on these two variability parameters, have been calculated.

To handle the correlation or dependency between the drill parameters (monitored and calculated), statistical methods, such as pattern recognition, neural networks, Fuzzy-Delphi-AHP technique, etc., have previously been used. Pattern recognition was used to separate coal, mudstone, and siltstone based on drill parameter responses in an open pit coal mine in Canada [23]. However, the capabilities of this technique decreases with the decrease in differences between rock types [24]. Neural networks were successfully used for drill monitoring data by [25]. The results were encouraging, but require detailed rock mass data to calibrate the model [24]. Saeidi et al. [26] combined the Fuzzy-Delphi-AHP technique and rock engineering systems (RES) to study rock mass drillability tribosystems. The technique is based on calibration using expert opinions, which is why the derived rock mass drillability index may be biased.

Another possible approach is to use multivariate techniques [24]. Principal component analysis (PCA) normally forms the basis for multivariate data analysis, and is often used for simplification of data tables, outlier detection, variable and object selection, correlation evaluation, classification, and predictions of different features [27]. PCA can transform the original variables into new, uncorrelated variables called components [28]. This paper uses PCA to analyse MWD data. One reason for using PCA is to try to determine the uncorrelated components that describe fundamental features within the drilling system and the rock mass. A commercial software, SIMCA (Sartorius Stedim Data Analytics AB, UMEÅ, Sweden) has been used for performing the PCA analysis. SIMCA uses the nonlinear iterative partial least squares (NIPALS) algorithm to obtain components [29]. After analyses, information has been shared with industry experts to validate the results.

3. Test Description

3.1. Test Site

LKAB's iron ore mine in Malmberget is the second largest underground mine in Europe. The mine is situated close to the municipality of Gällivare in the northern part of Sweden. The mine consists of about 20 ore bodies, of which 12 are currently being mined. The mining area stretches 5 km in the E–W direction and 2.5 km in the N–S direction. Large scale sublevel caving (SLC) is used for ore extraction. Figure 2a shows a layout of sublevel caving mining. Production boreholes are drilled upward in fan-shaped rings. Figure 2b shows an example of a fan containing eight boreholes. The number of the boreholes in a fan slightly vary in this case (from eight to eleven) depending on the shape of the ore body.
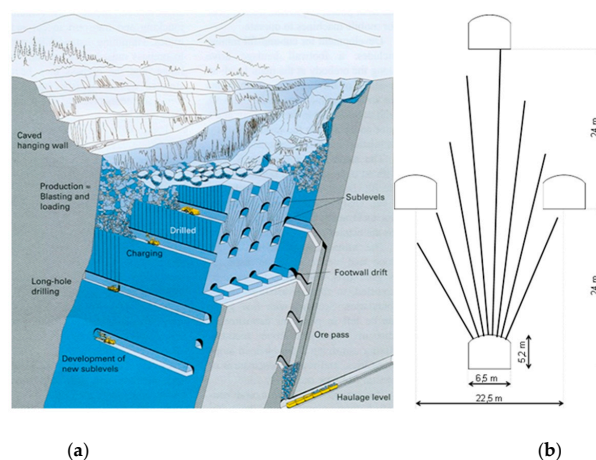

(**a**)　　　　　　　　　　　　　　　　　　　(**b**)

Figure 2. (**a**) Sublevel caving mining (courtesy by Atlas Copco); and (**b**) an example of a fan used in the Malmberget mine.

3.2. Drill System

In the Malmberget mine, fully-automated Atlas Copco SIMBA W6C drill rigs (Atlas Copco AB, Stockholm, Sweden) are used for all production drilling. These rigs are not equipped with standard top hammer rock drills, but with Wassara W100 hydraulic ITH hammers (LKAB Wassara AB, Huddinge, Sweden). Compared to pneumatic ITH hammers, the hydraulic hammers drill significantly faster, have less hole deviation, and generate less dust in the surroundings. Figure 3a,b show the components and stepwise mechanism of the Wassara W100 ITH hammer drilling system [30].
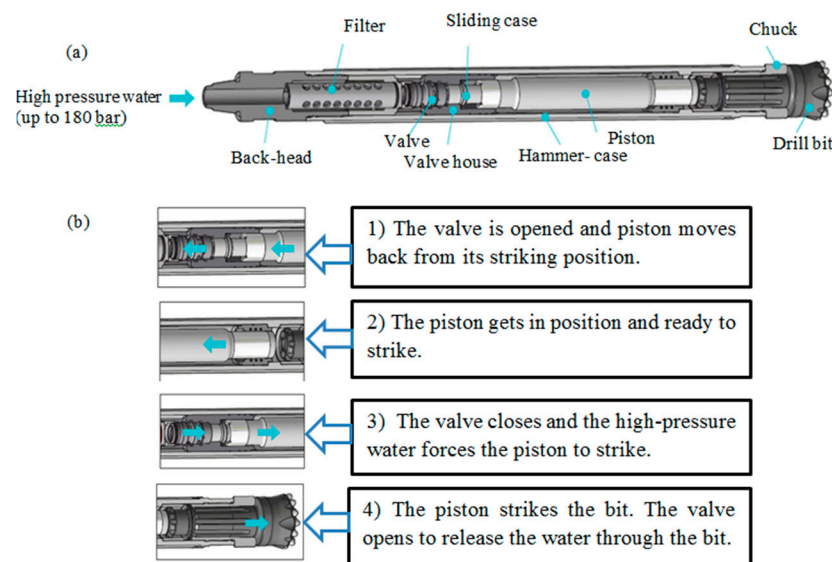

Figure 3. (**a**) Components; and (**b**) function of the Wassara ITH hammer [30].

For this drilling system, the hammer is positioned at the front of the drill string; energy is transferred through the drill string in the form of pressured water, mechanical torque, and mechanical feed force. The main task of the hammer is to convert the potential energy of pressurized water into an oscillating piston movement. The kinetic energy of the piston is transferred to the bit and, finally, into the rock. Rock fragmentation occurs at the highly-pressurized contact zones between the button bit and the rock. By rotating the bit, and thereby creating new impact positions for the buttons, new rock is fragmented and the penetration process continues. The debris is flushed away by the outlet water from the hammer, outside the drill string [31]. In Figure 3b, the valve is opened and the piston moves back from its striking position (step 1). In step 2, the piston takes the position to strike. In step 3, the valve is closed and high-pressure water forces the piston to strike. In step 4, the piston strikes the bit and the bit blows the rock. The valve is then opened to release the water through the bit [30]. For drilling 2.1 m, 102 mm extension rods are used. The cross-section of the rod and its specifications are presented in Table 1.

Table 1. Rod specification.

Parameter	Value
Outer diameter	102 mm
Wall thickness	8.8 mm
Length	2.1 m
Weight	54.4 kg

3.3. Drill Monitoring Technique

To monitor drill parameters, LKAB uses the Atlas Copco system. The system records and stores data at defined intervals (in this case, 3 cm) along the borehole. The drill parameters are the penetration rate, percussive pressure, feed pressure, rotation pressure, depth, and time (YYYY-MM-DDThh:mm:ss). The monitored data are transferred from the rig to the RRA (rig remote access) server by a wireless network.

3.3.1. Measured Parameters

The measured parameters can be divided into two groups: independent parameters and dependent parameters. Independent parameters, such as the feed pressure and percussive pressure, are controlled by the drill operation, while dependent parameters, such as penetration rate and rotation pressure, are responsive to the variation of rock mass properties [7,14,19,32].

- Penetration rate: This is the advance rate of the bit through the rock matrix; it is influenced by the geo-mechanical properties of the rock [33] and the applied forces. The parameter is measured by m/min.
- Percussive pressure: This refers to the water pressure used to force the piston to impact the bit [30]. The unit of the measured percussive pressure is bar.
- Feed pressure: The feed pressure generates feed force acting on the drill bit. The Atlas Copco rigs use a two-stage hydraulic cylinder to convert oil pressure into an axial feed force. The measurement unit is bar.
- Rotation pressure: This measure reflects the bit's resistance to rotation. In percussive drilling, the rotation is used to impact the new part of the bottom of the hole between successive blows. The movement between each impact is determined by the type, size, and geometry of the drill bit. The torque required to turn the bit mainly depends on bit resistance at the bottom of the hole and frictional resistance between drill rods and hole walls [6]. It is measured in bars.

3.3.2. Calculated Parameters

- Variability parameters: The penetration rate variability and rotation pressure variability have been used in field tests, with both parameters found to be sensitive to rock fracturing [21]. As shown in Equations (1) and (2), variability is calculated as the sum of residuals over a defined interval along the borehole:

$$PRV_i = \sum_i^{N+i} \left| \frac{\sum_i^{N+i} PR_i}{N+1} - PR_i \right| \tag{1}$$

$$RPV_i = \sum_i^{N+i} \left| \frac{\sum_i^{N+i} RP_i}{N+1} - RP_i \right| \tag{2}$$

where:

PRV_i: Penetration rate variability

RPV_i: Rotation pressure variability

N: Number of the intervals in a step = Total number of values considered in a step−1 (here, $N = 5 - 1 = 4$)

i: Index of the registered penetration rate or rotation pressure

PR_i: Registered penetration rate

RP_i: Registered rotation pressure

- Fracturing parameter: Fracturing is calculated by combining both variability of penetration rate and rotation pressure to make a robust parameter, which can improve prediction of rock fracturing [22]. It is measured by the Pearson residual [34], as shown in Equation (3):

$$Fracturing_i = \frac{1}{5}\left[0.5 \times \left(\frac{PRV_i}{\sqrt{\sigma^2_{PR}}} \right) + 0.5 \times \left(\frac{RPV_i}{\sqrt{\sigma^2_{RP}}} \right) \right] \tag{3}$$

where:

σ^2_{PR}:   Variance of registered penetration rate
σ^2_{RP}:   Variance of registered rotation pressure

4. Analyses and Results

For all drilling, there are hole length-dependent variations. However, depending on the drilling technique, this trend is more or less pronounced. It has been argued that, for ITH drilling, the penetration rate should not decrease with hole length, as the hammer is located at the end of the drill string acting directly on the rock. For pneumatic ITH drills, the drilling energy is provided by compressed air, flowing from the hole surface down to the hammer. As the length of the drill string increases, the pressure losses also increase, both inside and outside the drill tube, leaving less and less pressure to run the hammer. After the hammer, the air outlet is used for flushing, to remove cuttings from the face, and flush it back to the hole surface. This process will gradually become less efficient when the hole gets longer, causing a reduction in the penetration rate. For hydraulic ITH drilling, the above drawbacks are the same but are assumed to be less pronounced, because an incompressible medium is used.

Figure 4 shows the hole length trends for penetration rates at the test site. As expected, there is only a minor declining trend for the penetration rate with increasing hole length, an approximately 10% reduction over 40 m of drilling. For further analysis, the trend is removed, based on the regression line in the figure.

Figure 5 indicates the registered feed pressure versus hole length. For all drilling, an optimum applied feed force on the bit secures the contact between bit and rock throughout the entire impact. There is an increasing trend in the feed pressure with the hole length; more pressure is applied to compensate for the increasing drill string weight to maintain a constant force on the bit.
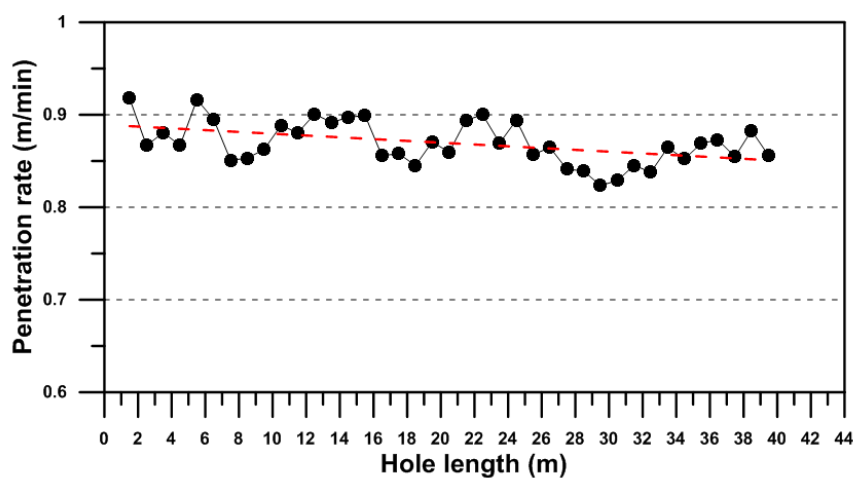

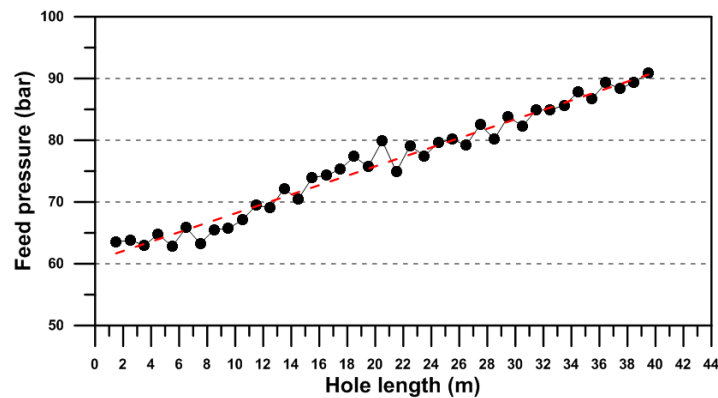**Figure 4.** Penetration rate versus hole length.

Figure 5. Feed pressure versus hole length.

Figure 6 presents the calculated feed force (based on the feed pressure and the geometries of the two-stage hydraulic feed cylinder) together with the theoretical counter-force generated by the increasing weight of the drill string, assuming a vertical hole. Recall that the specification for the extension drill rods appears in Table 1. The figure shows that the feed force is well balanced for the drill string weight when drilling vertical holes with an intended feed force of 20 kN. The problem is, however, that many holes are drilled in an inclined direction (see Figure 2b), particularly the side holes. To observe the effect of the different inclination of the holes on the calculated feed force, further studies have been carried out. The actual feed force acting on the bit is calculated for two boreholes inclined at two different angles. Figure 7 presents a force diagram showing the direction of relevant forces acting on the drill string for an inclined borehole ($\alpha < 90°$; case-1) and a vertical hole ($\alpha = 90°$; case-2). In this figure, the actual feed force acting on the bit (F_a) is the axial feed force generated by the cylinder (F_c; acting upward along borehole axis) minus the component of the force along the borehole (W sin α; acting downward along the borehole axis), which is generated by the mass of the drill string. Therefore, a variation of component force for different inclination of boreholes will have an influence on the actual feed force acting on the bit. To observe this influence on the actual feed force acting on the bit, two boreholes have been considered which are inclined at 60° and 90°. The actual feed force acting on the bit of the 60° hole is found slightly greater (about 7%) than that of the 90° hole, see Figure 8. However, the difference of the actual feed force for the inclined and vertical holes is not significant. In the following analysis, the feed force is normalised based on the regression line in Figure 5.
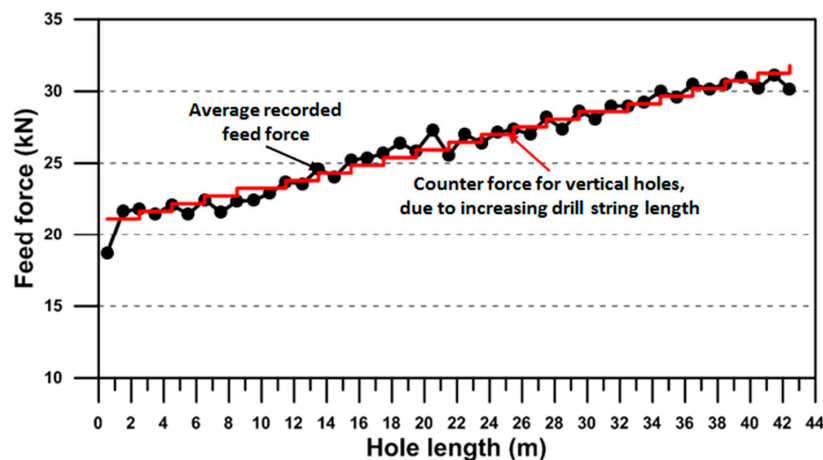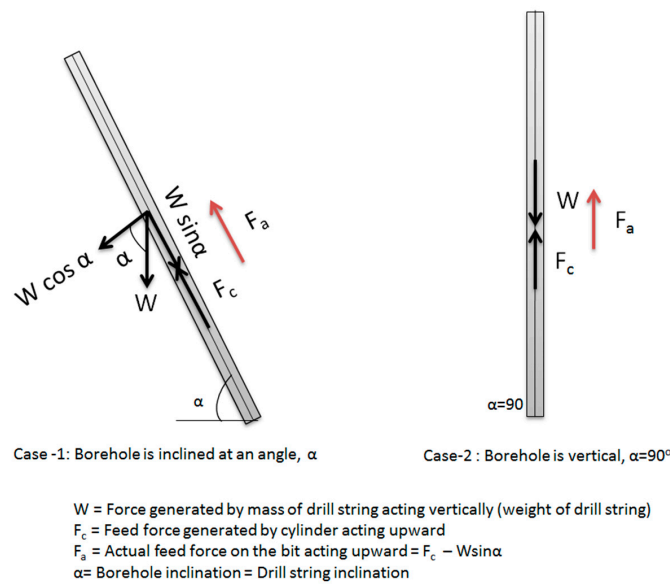

Figure 6. Feed force versus hole length.

W = Force generated by mass of drill string acting vertically (weight of drill string)
F_c = Feed force generated by cylinder acting upward
F_a = Actual feed force on the bit acting upward = $F_c - W\sin\alpha$
α = Borehole inclination = Drill string inclination
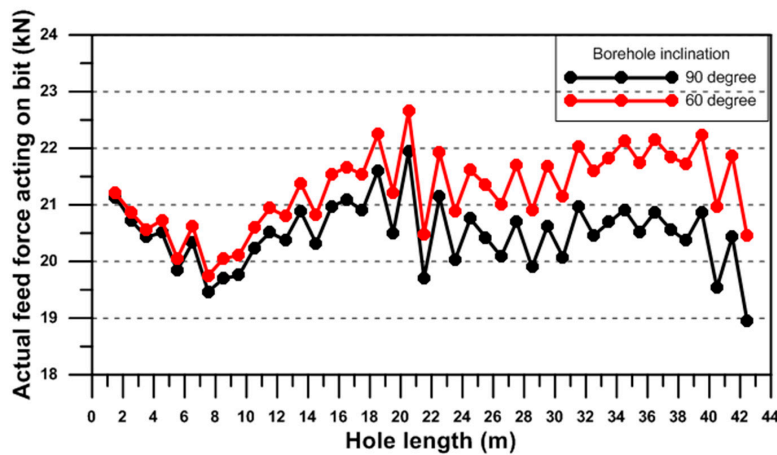
Figure 7. A force diagram.

Figure 8. Actual feed force versus hole length for different inclinations of the borehole.

Figure 9 shows the average rotation pressure versus hole length. The rotation pressure is almost constant to around 20 m length, at which point the curve shows an increasing trend. The buckling force of the drill string has a significant impact on hole deviations [35]. According to [36], a severely-buckled string could cause excessively crooked holes even in homogeneous formations. The buckling of a drill string under the action of gravity and axial thrust have been discussed in [37]. A number of different equilibrium helical buckling configurations for a tubing or drill string confined within a cylindrical casing or hole of larger radius and buckled under static compressive forces are determined by [37]. They obtained explicit and general solutions for the helical buckling of tubing and drill strings. The buckling force is the maximum force, which a column can carry while remaining straight. When the axial compressive force exceeds the buckling force, the column starts to bend. The Swiss mathematician Leonhard Euler calculated the buckling force for a long column in 1757 [38]. The assumptions and derivation of Euler's equation for different cases (based on constraints at the end of a column) have been mentioned by several authors [38–40].

The buckling force (Euler case 3, with one end fixed), F_k, can be calculated using following Equation (4) [35]:

$$F_k = \frac{2.05 \cdot \pi^2 \cdot E \cdot I}{l^2} \tag{4}$$

where:

    E = Young's modulus

    I = Area moment of inertia

    l = Hole Length

This equation was used assuming one end of the drill string is fixed and the other end of the drill string (bit inserts) is pinned. This means that the fixed end allows no translation and no rotation while the other end does not allow translation, but allows rotations.
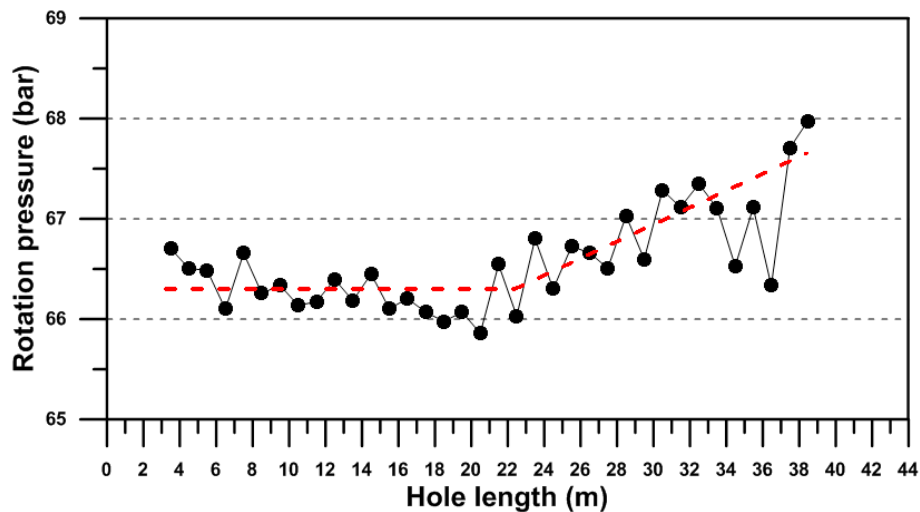

Figure 9. Rotation pressure versus hole length.

Figure 10 has the calculated buckling force versus hole length for the drill string used in the Malmberget mine. The applied feed force is also shown in the figure; it indicates that a buckling instability occurs at around 20 m of the drill string length. At this length, the contacts between the drill string and the hole walls will be initiated and will gradually increase as the drill string gets longer. This will generate an increased resistance to rotation, requiring increased rotation pressure, as shown in Figure 10, to maintain the pre-set rotation speed.
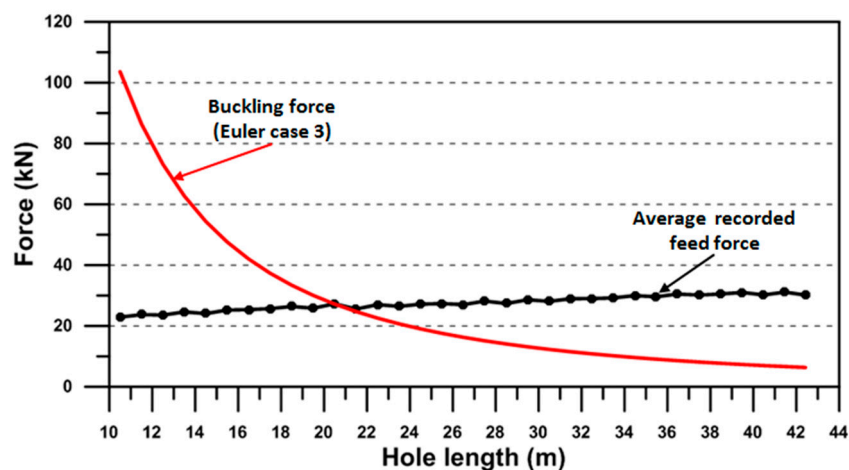

Figure 10. Drill string buckling force and applied feed force versus hole length.

Figure 11 presents the penetration rate versus the normalised feed force. The purpose of the feed force is to ensure that the percussive energy is efficiently transmitted to the rock. This means that the bit must be in constant contact with the rock throughout the entire impact. An additional

force is required to optimize efficient energy transfer from bit to rock and to ensure the rods are adequately threaded together. The relation between the penetration rate and feed pressure has been studied by several researchers [41–43]. Generally, the penetration rate increases with the thrust up to a certain level where the peak penetration rate is registered. After further increases in feed pressure, the penetration rate will again fall, until the drill finally stalls. This general behaviour is registered in this case study, showing an approximate optimal feed force between 24 kN and 28 kN. At a very low feed force, the penetration rate is also higher. This phenomenon has been reported by [6] which explains it as an inadequate contact between the bit and rock, causing free space movement. Further, as shown in Figure 8, the used feed force acting on the bit varies between 20 kN and 22 kN, for hole angles between 90° and 60°, which is lower than the optimum feed force between 24 kN and 28 kN. The actual feed force may, therefore, be increased to promote the overall penetration rate.
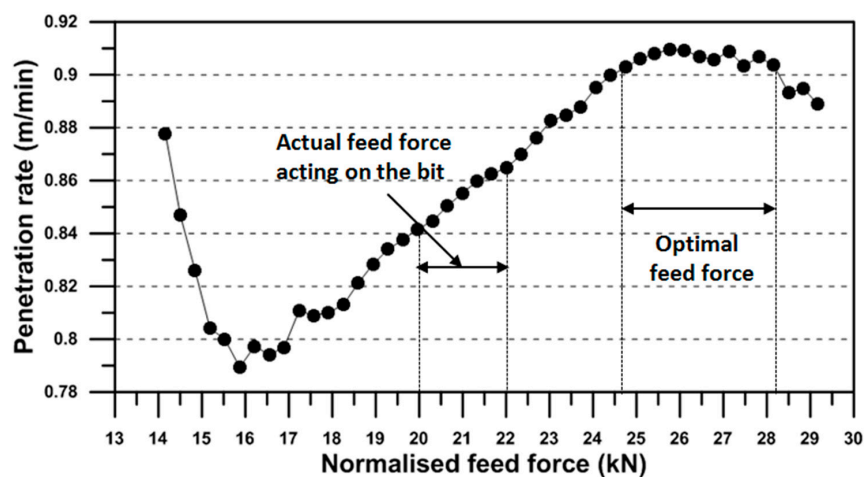

Figure 11. Penetration rate versus normalised feed force.

Figure 12 shows the rotation pressure versus normalised feed force. The purpose of rotation pressure is to ensure the rotation between successive blows. The rotation pressure required to turn the bit is dependent on the bit resistance at the bottom of the hole, as well as the frictional resistance between the drill string and the hole wall for long drill strings and at high feed forces [43]. According to [44], a definite relation between feed pressure and torque (rotation pressure) is found. The linear increasing rotation pressure versus feed force, seen in Figure 12, clearly indicates this relation.
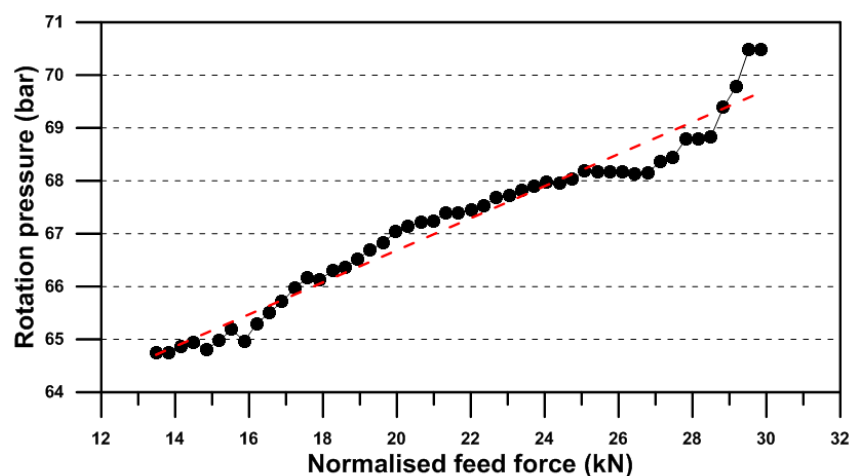

Figure 12. Rotation pressure versus normalised feed force.

As can be seen in Figures 9–12, the monitored drill response parameters are not independent, but highly correlated. Therefore, single parameter analysis or cross-plot analysis may not capture the complexity of monitored drilling data, especially their relation to varying rock mass characteristics.
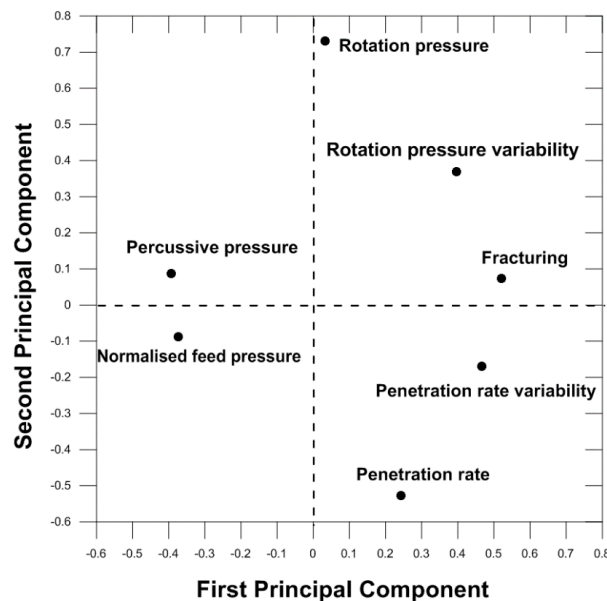

Figure 13. Loading plot of first and second principal components.

Due to the correlations, principal component analysis (PCA) is used for further analysis of all measured parameters, including penetration rate, percussive pressure, normalised feed pressure, and rotation pressure, and all calculated parameters, including penetration rate variability, rotation pressure variability, and fracturing. Figure 13 presents the loading plot for the first and second principal components.

The plane generated by the two components explains 62.2% of the total variation among all parameters. In Figure 13, the first component is dominated by the fracturing parameters (penetration rate variability, rotation pressure variability, and the combined parameter fracturing) to the right, and percussive pressure and feed pressure to the left. In modern drill systems, there is often a correlation between percussive pressure and feed pressure, even though the parameters are independent and are controlled by the rig control system. If feed pressure is reduced, it is important to control the percussive pressure to prevent damage to the drill system. The negative correlation between fracturing, on one hand, and percussive pressure, on the other, is interesting. When the rock mass condition goes from solid rock to increasingly fractured or broken, the percussive pressure reacts in the reverse way. In broken rock or in cavities, there may be insufficient feed force to maintain high water pressure, allowing water to flow more easily through the hammer. Overall, component 1 tends to be dominated by the drill system's response to the geomechanical properties of the penetrated rock mass.

Figure 14 presents the loading plot for second and third principal components. The loading plot captures 29.3% of the total variation among all included parameters. When the first component, presumably dominated by geo-mechanical rock mass condition, is removed, the second and third components may better represent the drill system. In the third component, there is some correlation between feed pressure and penetration rate. However, as seen in Figure 11, the positive correlation only relates to the zone between 18 and 24 kN; at lower and higher feed forces, the correlation is negative or non-existent.

The negative correlation between the penetration rate and the rotation pressure seen in Figure 13 seems non-existent in Figure 14. According to [14], the relation between the penetration rate and the

rotation pressure is complicated by rock mass properties. For example, rock fracturing that influences rotation pressure may positively influence the penetration rate if fracturing is moderate, but negatively if fracturing is severe, including stalling effects. In addition, penetration increases if the rock gets softer. Deeper penetration will increase rotation resistance and the corresponding rotation pressure. However, when the rock mass gets very soft, the bits may shear off the rock matrix instead of moving up, out of the hole, generated by the button of the bit, thereby reducing rotation pressure. Given this complexity, it is difficult to make definite conclusions when detailed rock mass descriptions are not available.
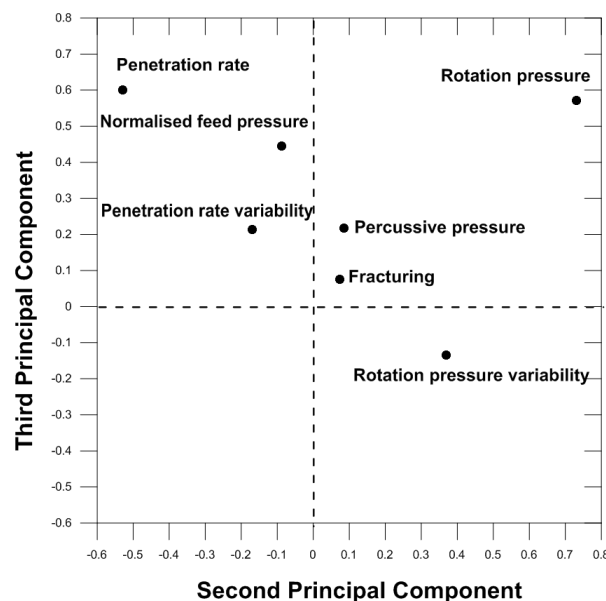

Figure 14. Loading plot for second and third principal components.

5. Conclusions

When trying to use the MWD technique to predict the characteristics of the penetrated rock mass, it is essential to have detailed knowledge of the drilling method and drill rig, including how monitored parameters relate to each other and to the penetrated rock mass conditions. Different drilling methods have different methods of excavation, and different sizes and dimensions of consumable materials (e.g., bit, hammer) will influence the drilling behavior and drilling response.

This paper has monitored a number of parameters of hydraulic ITH drilling and evaluated the data. The analysis finds a number of non-linear relations with root-causes in both the dimensions of selected consumables materials (e.g., bit, hammer) and the relation to the properties of the penetrated rock mass. In addition, principal component analysis (PCA) is found useful to separate the component related to geomechanical influences from the component related to drill system behavior only. Thus, the behavior of the drill system can be better identified and the system can be further improved for optimal drilling. The main findings are the following:

- There are linear hole length-dependent trends for the penetration rate and feed pressure. For the penetration rate, there is a marginal and decreasing trend. For the feed pressure, a large increasing trend is seen that is well balanced for the increasing drill string weight when drilling vertical holes upward.
- For rotation pressure, there is a step-wise linear trend; the rotation pressure is constant until around 20 m when the applied feed force is higher than the buckling force for the drill string. After this, the rotation pressure shows a linear increase with the hole length. It is important to consider this trend if rotation pressure is used as an input to the anti-jamming function of the rig.

- The optimal feed force is between 24 and 28 kN, higher than the used target feed force of around 20 kN. This suggests recording drill monitoring data can be an efficient way to optimize target values for optimal drilling.
- Principal component analysis (PCA) demonstrates how several drill parameters can be merged into a single component describing geo-mechanical influences on the drill response measurements.

Author Contributions: R. Ghosh analyzed the data and wrote the paper. H. Schunnesson and A. Gustafson have partly written and revised the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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