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OPTIMISATION OF THE ROCK DRILLING PROCESS CONDUCTED WITH SMALL-DIAMETER DRILLING TOOLS

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Abstract
This paper deals with rotary drilling into andesite in laboratory conditions, conducted on an experimental horizontal drilling rig. The processing of experimental data after the experiments contributed to the application and verification of mathematical models of penetration depth and torque as a function of the thrust force. The output is the identification of intervals of the applied thrust force levels for the efficient drilling zone. Designing of an optimisation algorithm for controlling the rock drilling process and monitoring the tool condition was based on changes in the thrust forces level at which specific energy reached minimum values. The criterion applied was the monitoring of the penetration depth, which together with the theoretical value of the torque defined the calculation of the specific energy values.

Keywords: *penetration depth, specific energy, optimisation algorithm*

1. INTRODUCTION

A description of the process of rotary drilling into rocks consists of the creation of mathematical equations describing mathematical correlations between the output variables and the controllable as well as uncontrollable input variables. The monitoring of input drilling parameters (thrust, rotational speed, flushing) and output drilling parameters is crucial for the purpose of identifying optimal operating parameters [1] and tool wear [2]. Due to significant variability of the properties of disintegrated rock, it is currently impossible to produce a mathematically accurate description of rocks and in in-situ conditions the drilling modes and performance of drilling tools vary. Many researchers have investigated the Measurement While Drilling (MWD) techniques and their possible application in the prediction of rock mass properties [3]. The importance of analysing and interpreting data obtained from drilling is equal to the importance of recording data for the purpose of creating mathematical models and algorithms for the development of artificial intelligence (AI) and big data technology [4], which optimise changes in the output parameters of the drilling process. Those parameters change since rocks are inhomogeneous and anisotropic materials. Higher efficiency of the process is based on reducing mechanical specific energy [5, 6]. Penetration rate is an essential indicator in a drillability analysis and estimation. This parameter is of great importance in mining projects. There are almost no models that can estimate the penetration rate for core drilling operations [7]. A focus of the research presented in this paper is the optimisation of core drilling by applying a mathematical model of penetration depth [8] and torque as a function of the magnitude of the thrust force applied, with the use of data obtained after drilling into andesite in laboratory conditions.

2. EXPERIMENTAL

A series of experiments, conducted during the drilling into andesite, confirmed a trend similar to that shown in Figure 1. Experimental samples were rectangular blocks sized 150 x 150 x 300 mm. The testing was carried out with three diamond core drill bits: a 16/25 drill bit; a 12/18 drill bit; and a 25/35 drill bit. They only differed in sizes of the diamonds embedded. In total, 116 experiments were carried out and the drilled length was 35.95 m. Drilling modes applied were those with a constant rotational speed (500 rpm; 1,000 rpm; 1,500 rpm; and 2,000 rpm) and a gradually increasing thrust force value (0–20 kN). Although the application of drilling modes with a constantly increased thrust force at a constant rotational speed was not particularly appropriate in terms of the drill bit service life, it facilitated the creation of models describing the changes that occurred in the rock-tool interaction zone. Figure 1 shows a correlation typically applied in studies dealing with drillability.

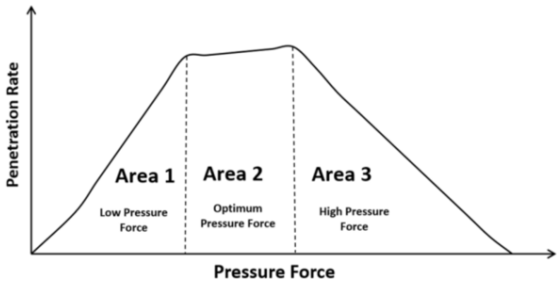

Figure 1. Corelation between the penetration rate and the pressure force

As the pressure force increased, the penetration rate also increased. An optimal penetration rate was achieved at a certain pressure force, while after that point was exceeded, the penetration rate decreased as the pressure force increased.

2.1 Theoretical background

The energy consumption of the drilling process is identified using the values of specific energy SE ($MJ.m^{-3}$), which was introduced into the drilling research by Teale [9]. It expresses the amount of energy necessary to break a unit volume of rock. Equation 1, a mathematical expression of specific energy,

$$SE(F) = \frac{2\pi\, T(F)}{A.\ p(F)} \qquad (MJ.m^{-3}) \tag{1}$$

clearly shows that the variable parameter in that equation is $\frac{T(F)}{p(F)}$, wherein T (Nmm) is the torque and p (mm) is the penetration depth as a function of the thrust force F (N). In the equation, A (mm^2) is a constant expressing the surface area of the contact surface between the tool and the rock. The mathematical model of torque T (Nmm) is described in Equation 2, which represents, for an astatic system, the solution of a second-order differential equation with constant coefficients:

$$T(F) = \kappa \left[F + \Theta\left(e^{-\frac{F}{\Theta}} - 1\right)\right] \qquad (N.mm) \tag{2}$$

wherein F (N) is the applied thrust force. The substitution coefficient κ (mm) expresses a linear response of the torque to the growing thrust force; and θ (N) represents a delay in the response of the drilling set at low thrust force values. The mathematical model of penetration depth p (mm) as a function of the thrust force F (N) is the solution of the second-order differential equation with constant coefficients [8]:

$$p(F) = p_{max}[1 - e^{-\omega.F}(1 + \omega.F)] \qquad (mm) \tag{3}$$

wherein F (N) is the applied thrust force, p_{max} (mm) is the maximum penetration depth to which the equation solution converges, and ω (N^{-1}) is the substitution coefficient. After the substitution of Equation 2 and Equation 3 to Equation 1, the resulting mathematical model of specific energy was as follows:

$$SE(F) = \frac{2\pi}{A} \frac{\kappa\left[F+\Theta\left(e^{-\frac{F}{\Theta}}-1\right)\right]}{p_{max}\left[1-e^{-\omega F}(1+\omega F)\right]} \quad (MJ.m^{-3}) \; . \qquad (4)$$

The second derivative of penetration depth Equation 3 with respect to thrust force determines the inflection point F_{inf} of the p-F curve: $F_{inf} = \frac{1}{\omega} \quad (N)$ (5)

The inflection point values were calculated for all of the executed andesite borehole drillings. Since the inflection point F_{inf} determines the area of the efficient rock disintegration by chipping, this efficient area continuously moves towards higher thrust force values with an increasing total drilled length due to continuous wear of the drill bit. Mathematical models *p(F)* and *T(F)* were used for calculating the lower limit F_{inf} and the upper limit $F_2 = 2.F_{inf}$ of the trust force values that delimitate the efficient drilling area, in which, in theory, specific energy is minimal. Also, the optimal thrust force area F_w was identified for each drilling into andesite, as calculated using Equation 6, wherein $|\varepsilon| = \frac{|\theta|}{F_{inf}}$.

$$F_w = \frac{1}{2}\left[|\theta|(1-|\varepsilon|)+F_{inf}\right] + \sqrt{|\varepsilon|.\theta^2\left(\frac{1}{4}.|\varepsilon|-\frac{1}{2}\right) - F_{inf}\left(\frac{3}{4}.F_{inf}+\frac{1}{2}.|\theta|\right) - \frac{1}{4}.\theta^2} \qquad (6)$$

The thrust force values, calculated using Equation 6, were used to calculate the optimal thrust force values, which ranged in the interval $F_w \in$ <1.37;1.66>, while the average value, calculated with the use of all drillings and tested drill bits, was $F_w \cong 1.45\ F_{inf}$.

3. RESULTS AND DISCUSSION

For all of the drill bits tested, the results showed that the difference between the values of specific energy at thrust force values F_w and F_2 was negligible. However, the penetration rate at thrust force F_2 was higher while the energy-intensity of the process was practically unchanged. Those axioms were used as the basis in the process of designing an optimisation algorithm presented in Figure 2.

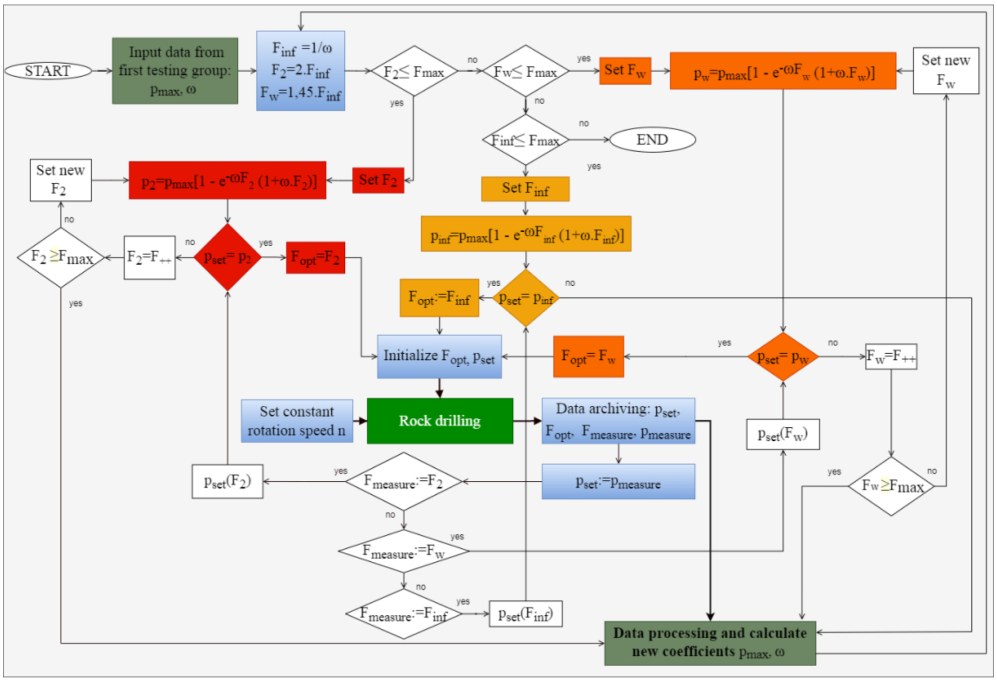

Figure 2. Optimisation algorithm

The newly-designed algorithm, shown in Figure 2, monitors dynamic properties of the process of experimental drilling with the use of the identified solution of the differential equation for a mathematical model of the p-F curve – Equation 3, in particular by identifying substitution coefficients ω and p_{max}, as well as its higher derivations, based on the thrust force value – Equation

5. That facilitates efficient control of the drilling process by simply changing the magnitude of the applied thrust force to the optimal value F_{opt}. In the case that the identification criterion (penetration depth) is not met, as verified by the online control in experimental drilling, it is necessary to identify a new optimal thrust force level using the mathematical model of the p-F curve for calculating new substitution coefficients as a response to the dynamic property of the process of a changing condition of the tool with an increasing drilled length. In such a case, the calculation of a new optimal thrust force level is based on the archived data obtained in experiments conducted with a gradually increasing thrust force and a constant rotational speed. Similarly, the first adjustment of the optimal thrust force level is preceded by the creation of trial experimental drillings and data processing.

4. CONCLUSION

The analysis of the used mathematical apparatus revealed simplicity of the solution aimed at optimising the drilling process in terms of minimising energy intensity of drilling into rocks. Yet, numerous publications indicate that there is a linear correlation between specific energy and wear intensity (wear degree per drilled length), which is primarily affected, as to the resulting values, by the abrasiveness of the rock drilled. As a result, the minimisation of energy intensity of a rock drilling process leads to a significant increase in the lengths drilled, and hence to the extension of the service life of the drilling tool.

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