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RESULTS FROM EXPERIMENTAL RESEARCH OF ROCK BREAKING BY SMALL DIAMETER DIAMOND CORE DRILL BITS

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Abstract
The rock drilling process involves a wide range of factors that affect it to varying degrees, and this influence is then reflected in the output parameters. It is complicated to predict them and to determine the degree of their impact on the rock breaking efficiency. In order to simulate the real drilling process without the impact of the drill string, a horizontal laboratory drill rig was designed and constructed at the Institute of Geotechnics of the Slovak Academy of Sciences. The goal of experimental research on a test facility is to provide accurate and immediate information in real time and, based on their evaluation and analysis, to identify parameters that significantly affect this process. The article presents our findings from experimental research on diamond core drill bits.

Keywords*: rotary drilling, experimental drill rig, drill bit, wear, rock, specific energy, optimization,*

1. INTRODUCTION

The rock drilling performance is affected by the constructional and performance parameters of the drilling equipment and the drill bit, the parameters related to the drilling process and the parameters related to the properties of the drilled rock [1]. For the purpose of evaluating the impact of changes in various combinations of the operational parameters on the potential financial and operational benefits of the drilling operations, multiple studies have been conducted [2]. In order to accurately determine the factors that enter the drilling process and identify their impact on the rock breaking efficiency, the process must be subjected to experimental research. The studies on rock breaking by drilling, conducted in laboratory conditions, improve our understanding of the interactions between the rocks and the drill bits and provide the information required for the purpose of evaluating and optimally controlling the drilling process in terms of the drilling performance and energy consumption, which may significantly reduce the costs.

2. EXPERIMENTAL RESEARCH

In order to accurately determine the key factors that enter the drilling process and to identify their impact on the rock breaking efficiency, the drilling process was subjected to experimental research. At the Institute of Geotechnics of the Slovak Republic, an experimental laboratory drilling rig was designed and constructed for the simulation of a real drilling process without the influence of the drill string. The test device is intended for horizontal drilling with small-diameter bits up to a diameter of 70 mm, commonly used in industry. Diamond or carbide core drill bits were used for research purposes. The rock for experiments was treated using a circular saw for rock cutting. The tested samples were approximately cuboid-shaped with dimensions of approximately 150x150x300 mm. Water without any additives was used as the flushing fluid. It was supplied by a pump from a water tank with a quasi-constant flow rate $10^{-3}.m^3.s^{-1.}$ Position measurement switch allowed rock specimen drilling up to 260 mm length.

The experiments carried out on this device were intended to improve our understanding of the interactions between the drilled rock and the drill bits, to examine of the effect of a drilling mode on the course of the rock drilling process, to investigate the rock drillability, to study the energy consumption in drilling, to assess the tested drill bits in terms of their usability in real operating conditions, to determine the effect of rock changes, rock drilling mode and drill bit on vibrations generated during rock drilling, to determine the relationship between the drill bit wear and energy requirement for the rock drilling, to investigate the relationship between the drilling tool, the applied drilling mode, energy demands in breaking and the characteristics of drilled rock debris.

The device is equipped with an on-line measurement system, that enables continuous data acquisition and archiving, controls and monitors the experiment, provides measured values of process parameters in the form of time changes – electric current, thrust force, rotation speed, torque, enables online visualization of the torque and three orthogonal components of cutting forces, provides values of vibration acceleration in three orthogonal directions and their visualization, records the drilled length and calculates the drilling speed and specific energy using the pre-defined equations from the monitored data. It is equipped with a system that captures crushing products – drilled rock debris, which are then used for further analysis.
The measured data was used to calculate the advance rate and specific energy in real time during drilling. These values enabled the quantification of the rock drilling efficiency.

3. RESULTS FROM EXPERIMENTAL RESEARCH

3.1 Determining the zone of efficient drilling

Based on the experiments performed and the processing of the obtained data, a mathematical model of penetration depth as a function of the thrust force was derived [3]:

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

where 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.
Mathematical model of p(F) exhibited a very high correlation tightness between the experimental and theoretical values in all 116 evaluated experiments, with a correlation coefficient value higher than 0.97.

Through gradual mathematical adjustments, equations were derived for calculating the limit values of thrust forces and penetration depths defining the zone of efficient drilling. The optimal thrust force was identified at which the specific energy curve reaches the minimum at a relative high rock breaking efficiency.

The highest probability of efficient drilling (chipping) occurs near of inflection point F_{inf} of the penetration-thrust curve. The most intensive deceleration of an increase in the penetration depth was observed at the F_{up} thrust force value (the upper boundary of the zone of efficient drilling) which was twice the F_{inf} value (the lower boundary). The relationships were derived for calculating penetration depths corresponding thrust F_{inf}, F_{up} and F_{opt}.

The analysis of the used mathematical apparatus revealed the simplicity of the optimization of the drilling process in terms of the minimization of energy consumption. This requirement was met when the drill bit operated at a low value of specific energy by controlling the penetration depth in the zone of efficient drilling. Figure 1 shows the limit values of thrust force and penetration depth defining the zone of efficient drilling in terms of minimum specific energy values.

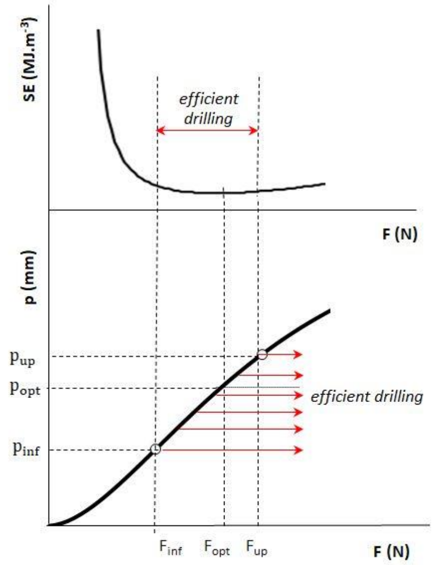

Figure 1. Limited values of thrust force and penetration depth determining the zone of efficient drilling with regard to the minimum values of specific energy.

3.2 Determination of drill bit wear using 3D optical technologies

In the segment of research into rock drilling, there is a growing need for state-of-the-art monitoring, documentation and efficient evaluation of wear of drill bits by applying contactless measurement methods [4]. One of them is the use of 3D technologies – 3D scanning, photogrammetry and the use of software to process the created 3D models. Figure 2 illustrates the results of the wear evaluation of the small-diameter surface-set diamond drill bit of the outer diameter of 46 mm. The 3D model was created by scanning with a Discovery microscope. Microscope facilitated the acquisition of sufficiently detailed data for the purpose of processing them in CloudCompare software. Fig. 2a) shows the surface of the drill bit before evaluation. Fig. 2b) shows the worn surface after evaluation by the software, scaled in colour. Fig. 2c) presents the scanned surface after the experiments. The drill bit exhibits asymmetrical wear as a result of the mechanism used for fixing the drill bit on the thread. Threads of the fixing mechanism and the contact surface of the drill bit were moderately worn caused by drilling. The bit drilled three samples of granodiorite with a total length of 480 mm and two samples of limestone with a total length of 400 mm. When drilling the limestone, the following settings were used: thrust force 17 kN; rotation speed 1000 rpm. For granodiorite, the rotation speed was 1000 rpm and the thrust force was increased from 10 kN to 14 kN due to faster wear of the drill bit.

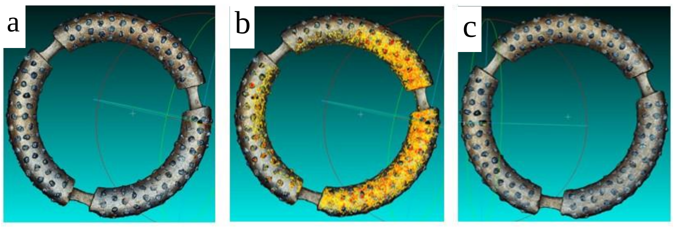

Figure 2. Colour-scaled wear of the surface of the surface-set diamond drill bit; drilled length 480 mm granodiorite and 400 mm limestone

The 3D method for identifying the bit wear, compared to conventional methods, such as weighing and measurement, is more accurate and provides a much wider range of outputs, such as wear distribution, more accurate calculation of material volume removed between the individual measurements, and colour scaling based on the wear quantification. The method may also be applied to impregnated and hard-metal small-diameter drill bits, provided that some of the procedures are adjusted.

3.3 Vibration signal for assessing the drilling process

Our research is also focused on alternatives for the use of vibrations for the control of the drilling process. We used experimental laboratory measurements to determine the effect of applied regime changes on vibrations. It has been shown that vibration acceleration values responded quite sensitively to changes in thrust force and increase linearly with rotation speed. The found correlation of the specific energy with the inverse of the average effective vibration acceleration values in the direction of the drilling axis as a function of the rotation speed, provided a prerequisite for the use of the vibration signal for the optimization of the control of the drilling process in terms of the maximum tool life and therefore the minimum wear intensity. From the processing of the recorded vibration signal in the frequency domain, it can be concluded that the rock grain size is probably the decisive characteristic affecting the intensity of the vibration signal.

Based on the recorded and subsequently processed vibration signal from experimental drilling, it was confirmed that the induced vibrations carry the information about the current state and conditions of drilling and that each applied drilling mode, as well as the drilled rock, has a specific vibration response.

3.4 Use of drill debris for drilling process assessment

Laboratory drilling rig was adjusted for collection of drill debris from flushing fluid aiming to involve the drill debris characteristics into the drilling process assessment. Roughness index CI was used for changes in grain size, determined by sieve analysis of the drill debris. Complex analysis of drilling process effect on shape, size and distribution of drill debris was performed using the dynamic image analysis instrument Camsizer X2.

Analysis of rock debris will provide new useful information to monitor the cutting capability of the drill bit. The size and shape of drill cuttings fragments are related to the rock breaking mechanism and the energy consumption of the drilling process.

4. CONCLUSION

The long-term experimental research of rock drilling running at the Institute of Geotechnics SAS has been focused on the study of rock-tool interactions. Most of the knowledge gained from research of small-diameter diamond drill bits, carbide drill bits and chisel drill bits has been processed into comprehensive mathematical models that allow generalization of rock breaking processes for a wide range of different types of drilling tools. This created the basis for exact optimization procedures for these processes.

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