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IMPACT OF CLEANING EFFICIENCY ON DISC CUTTER DRILLING PERFORMANCE

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ABSTRACT
Large diameter drilling operations, including tunnel boring and raise boring, are capital-intensive projects. As such, proper estimation of time and cost is critical to the planning of the drilling project. To arrive at the correct estimation of the drilling time during the drilling phase, accurate prediction of the drilling performance is needed. In large diameter applications, disc cutters are the primary cutting tools, hence, several investigations have focused on developing accurate estimation of disc cutter forces. Other studies have also sought to understand the impact of rotary speed and cutter geometry on drilling performance. This study seeks to contribute to existing body of knowledge by evaluating the impact of cuttings cleaning efficiency on disc cutter drilling performance. This technical paper presents the results of two sets of drilling experiments. Both experiments were conducted under atmospheric condition on the same granite block using same rotary cutting machine and tri-disc disc cutter with tungsten carbide inserts. Same drilling parameters were applied during each of these experiments. However, the difference lay in the adopted cuttings evacuation method. One drilling procedure adopted the dry method wherein the cuttings were evacuated with vacuum while in the second procedure, the cuttings were cleaned using the jetting action of a high spray nozzle. The results of these experiments show how much influence the cleaning efficiency has on the disc cutter drilling performance.

Keywords: Disc cutter, drilling performance, cleaning efficiency, rotary cutting machine.

NOMENCLATURE

ρ_b	Bulk Density (kg/m^3)
ν_p	Compressive Wave Velocity (m/s)
E'	Dynamic Modulus (GPa)
σ_t	Indirect Tensile Strength (MPa)
E	Modulus of Elasticity (GPa)
σ_{PLI}	Point Load Strength Index
ν	Poisson Ratio
ROP	Rate of Penetration (cm/min)
ν_s	Shear Wave Velocity (m/s)
T	Torque (Nm)
UCS	Unconfined Compressive Strength (MPa)
WOB	Weight on Bit (KN)

1. INTRODUCTION
There are three significant kinds of mechanical drilling - rotary drilling, sonic drilling, and rotary percussion drilling. A static WOB is applied to the rock in rotary drilling alongside the rotary drilling's planned rotary speed and flow rate. Rotary Drilling finds wide application in the following areas: Oil and Gas Drilling, Surface Mine Blasthole Drilling, Diamond Core Drilling, and Large Diameter Drilling (with Tunnel Boring Machine, TBM, and Raise Boring Machine). While the standard Oil and Gas drilling bit sizes range from 6 inches (152.4mm) to 28 inches (711.2mm) [1], the diameter of the drilled holes under Large Diameter Drilling is in magnitude of meters.

Large Diameter Drilling finds applications in mining, energy, marine, and construction [2,3]. Given these large diameter drilling applications, operators can drill both soft and hard formations. Some solids' mineral mining activities may involve drilling large diameter holes into quartz veins (quartz, a crystalline mineral) known to have an absolute hardness of 10 on the Mohs' hardness scale [4]. Disc cutters are the dominantly used cutting tools on large diameter drilling machines (TBM or RBM).

Rock excavation performance optimization remains a concern despite the hole drilled or the rock (or soil) excavated. Rock excavation cost makes a significant contribution to the project cost. Amado indicated that in 2010, it could cost 55-88million USD to drill one offshore exploration or appraisal Oil and Gas well [5]. Drilling a hole necessitates the use of hydraulics to clean out the cuttings. Drill cuttings removal is critical during drilling to ensure drilling depth and efficiency. It cannot be over-emphasized how crucial it is to have a good understanding of wellbore hydraulics during drilling [6]. The case is not different in a large diameter drilling operation. To prepare a realistic project cost and time estimate, the operator estimates the performance of the mechanical excavator during the project planning phase. An accurate understanding of the impact of cuttings cleaning on disc cutter drilling performance ensures that the rock excavation project will have reduced costs and time overruns. Avoiding cost overruns is especially important given the high capital costs that are associated with rock excavation.

Many investigators have studied hole cleaning in relation to how it impacts drilling rate with depth. Maurer [7] evaluated the effect of cuttings cleaning on ROP as seen in Figure 1 below. In his study, ROP varied directly with the rotary speed and to the square of WOB. It also varied inversely to the bit diameter squared and the square of the strength of the rock being drilled. Maurer [7] suggested that the condition where all of the rock debris is removed between tooth impacts indicates perfect cleaning.

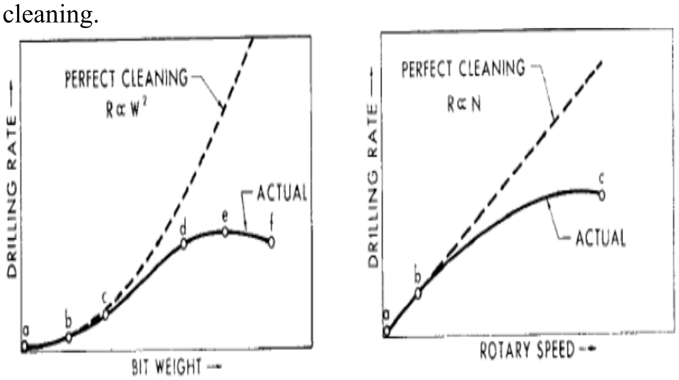

FIGURE 1: MAURER'S [7] STUDY ON ROP-WOB-SPEED RELATIONSHIPS

2. MATERIALS AND METHODS

2.1 Drilling System

The Drilling Technology Laboratory (DTL) at Newfoundland has a Large Drilling Simulator (LDS) in place to conduct different drill-off tests using a Disc Cutter. The Large Drilling Simulator provided rotary torque and WOB for the drill-off tests. Up to 40KN WOB could be applied with the LDS. The torque limit of this system is to be 1100Nm, while the limit of the rotary speed is 1000rpm. The LDS simulates actual rotary drilling operations.

The LDS has five major integrated systems:

- Power System
- Hoisting System: consists of two pneumatic cylinders, a hydraulic servo-actuator, one load cell, accelerometers, and magnetostrictive displacement transducers. This system applied the WOB required for drilling and measured the axial displacement.
- Rotary System: high torque motor
- Pumping System – water was circulated through the pumping system of the LDS in order to clean out the cuttings. Figure 2 shows the LDS system.
- Data Input and Acquisition (DAQ) System: With the LabView Manager integrated into the LDS, drilling parameters (WOB and Rotary Speed) were inputted into the LDS. Conversely, the measured data of the drill-off tests were obtained through the Data Acquisition System [8].

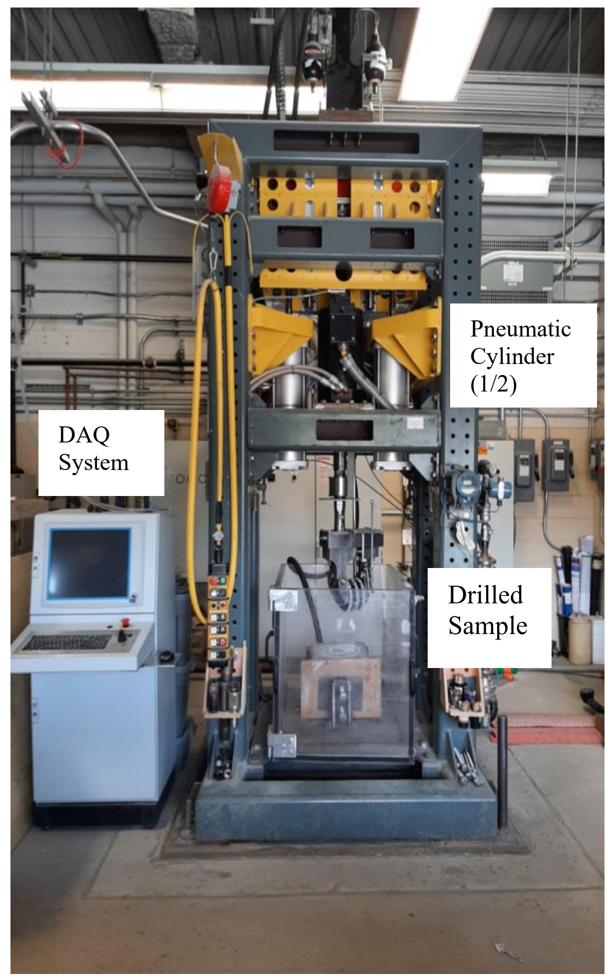

FIGURE 2: LARGE DRILLING SIMULATOR

2.2 Cutting Tool (Disc Cutter)

The cutting tool used for the experiment is a cylindrical triple-disc cutter (shown in Figure 3 below) with a pressure compensator with the following features shown in Table 1 below.

TABLE 1: OVERVIEW OF THE DISC CUTTER USED

S/N	Overview	
1	Number of Discs	3 (in an integral body)
2	Diameter	180mm
3	Cutter Type	Tungsten Carbide Inserts in a Matrix Body
4	Height of insert	5mm
5	Max Allowable WOB	69.9KN

FIGURE 3: CYLINDRICAL DISC CUTTER

2.3 Rock Sample (Granite)

Granite is a plutonic igneous rock that is hard and brittle [9]. It is coarse-grained igneous rock that consists mainly of quartz, alkali feldspar, and plagioclase [10]. Before these drill-off tests, an investigator with the DTL carried out X-ray Diffraction Analysis on a granite core sample [11]. This X-ray Diffraction analysis is complementary to the suite of tests carried out as part of the material characterization of designated rocks. Table 2 shows the mechanical properties of the drilled granite rock.

TABLE 2: COMPOSITIONAL ANALYSIS AND MECHANICAL PROPERTIES OF GRANITE

Property	Number of Samples Tested	Mean	Standard Deviation
ρ_b (kg/m^3)	24	2900.63	34.46
UCS (MPa)	7	168.40	7.54
E (GPa)	7	13.31	2.31
ρ_b (m/s)	5	5480.91	109.34
v_s (m/s)	5	3433.19	53.97
E' (GPa)	5	81.14	1.43
ν	5	0.18	0.03
σ_t (MPa)	14	16.27	2.56
σ_{PLI} (MPa)	20	14.17	0.69
CAI	5	4.16	0.47
Mineral Composition	Anorthite (61.4%), Actinolite (22.4%), Muscovite (13%) and Quartz (3.2%)		

2.4 Cuttings Evacuation Techniques

For this study, the objective is to investigate how different cuttings cleaning methods impact the disc cutter drilling performance. As such, the same rock sample and the drilling setup were used for each drill-off test. The two main methods utilized for cuttings cleaning and removal include (i) Dry Cleaning (ii) Wet cleaning.

Wet Drilling Method

In the wet drilling setup, two flat high-pressure spray nozzles (Figure 4) were used to clean the cuttings generated under the disc cutter. Fresh tap water at atmospheric pressure was circulated through the LDS pumping system to remove the cuttings. Table 3 below shows the spray nozzles' specifications.

TABLE 3: SPRAY NOZZLES' SPECIFICATION

	Spray Nozzle 1	Spray Nozzle 2
Part Number	3234K996	3234K979
Angle (Degrees)	15	15
Connection	$\frac{1}{4}$ NPT Male	$\frac{1}{4}$ NPT Male
Max Flow Rate (gpm)	13.7	11
Max Pressure (psi)	300	300

FIGURE 4: INSTALLED HIGH-PRESSURE SPRAY NOZZLE

Dry Drilling Method

For dry drilling setup, a vacuum system was utilized for cuttings evacuation. Thus, no drilling fluid was circulated in the dry drilling run. The crushed rock cuttings were vacuumed out of the rock surface using a 16US Gallon 6.5HP Vacuum cleaner with a 20.53m length hose (Figure 5 below). This method of evacuation was assessed to carry some risk especially when experiencing increased vibration while drilling at increasing WOB values.

FIGURE 5: A 16US GALLON 6.5HP VACUUM CLEANER FOR CUTTINGS EVACUATION

2.5 Drilling Matrix

The drilling matrix for each drill-off test is shown in Table 4 below.

TABLE 4: DRILLING MATRIX

Offset Distance (cm)	Applied Rotary Speed (rpm)	Applied WOB (KN)	Water Flowrate for Wet Drilling (litre/min)
6	10.0	7.2	11.5
		10.0	
		12.1	
		14.6	
		17.0	

For both sets of experiments (wet and dry drilling), the drilling setup and the drilled rock were the same. As the only varied aspect is the cleaning mode, the applied drilling parameters were kept the same too. Both drill-off tests were carried out at a constant rotary speed while varying the applied WOB. The offset distance of the disc cutter from the center of drillstring rotation is 6cm.

3. RESULTS AND DISCUSSION

As drilling progressed, the drilling data were recorded by the Data Acquisition System at a frequency of 100Hz. As such, a significant quantity of data was collected and analyzed in order to understand the drilling performance for each drilling run. The outputted drilling data included vertical displacement, time, and drilling torque. The recorded data also showed the bit-rock interactions, confirming the applied rotary speed, WOB, and presence or absence of drilling vibrations. Two major indicators, the rate of drilling penetration and drilling torque, were used to evaluate the drilling performance for each adopted mode of cuttings cleaning. Drilling penetration rate is the slope of the plot of the recorded vertical displacement (when the disc cutter is on bottom) against the cumulative drilling time. A sample plot is shown in Figure 6 below. The plot indicates a general upward increase in vertical displacement as drilling progressed. The rate of penetration in the plot below is 0.0385cm/min.

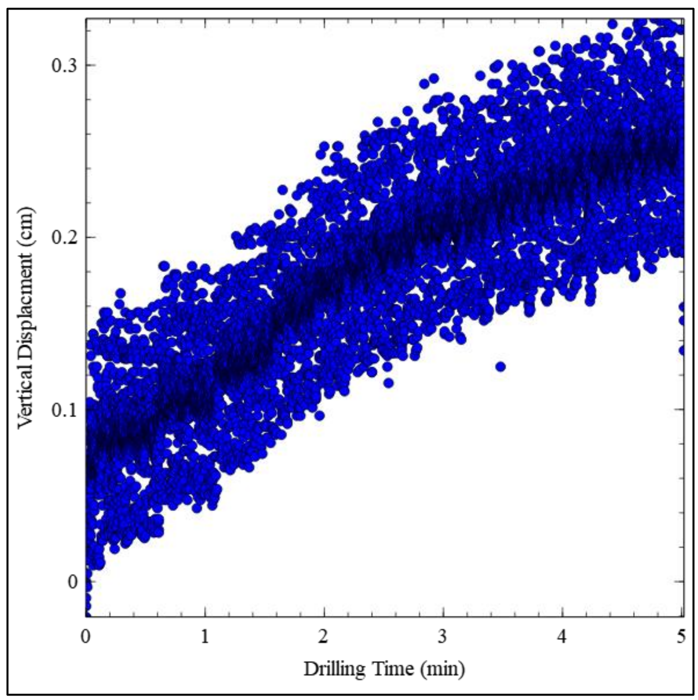

FIGURE 6: DISPLACEMENT-TIME PLOT (17.0KN, 10RPM)

Figure 7 shows the results of the drill-off tests for both modes of cuttings cleaning. From Figure 7, it can be seen that the ROP increased with increasing WOB. One key feature of wet drilling is the cooling effect of the water on the cutting tool. In addition, the jetting water flushed the rock cuttings completely away from the rock surface enabling the disc cutter to engage a fresh rock face. Figure 7 shows that the rate of penetration decreased with increasing WOB.

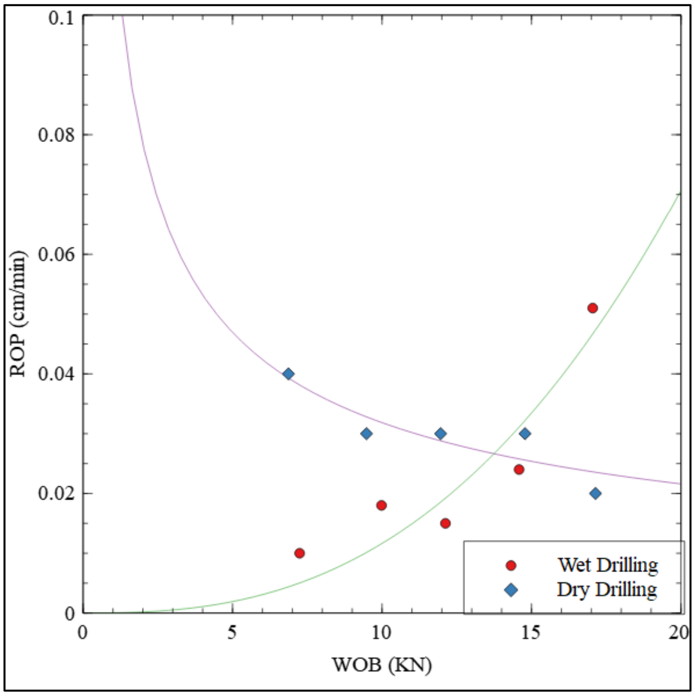

FIGURE 7: ROP VS WOB (WET DRILLING AND DRY DRILLING)

The drilling torque for each applied drilling parameter was recorded. The average drilling torque was computed for each drilling step. Also, the standard deviation was computed to evaluate the variability of the collated data. Increased drilling torque indicates better rock-cutter interaction as is shown by Maurer [7] in Equations 1 (for perfect cleaning) and 2 (for poorer cleaning).

$$T \propto WOB^2 \tag{1}$$

$$T \propto WOB^{1.5} \tag{2}$$

Figure 8 shows the plot of the average recorded torque for the wet and dry drilling. From Figure 8, it can be seen that the drilling torque for wet drilling was always higher than the drilling torque for dry drilling at the lower WOB values. This indicates that there is more bit-rock interaction because of better cuttings evacuation.

Thus, Figures 7 and 8 show a clear distinction between the drilling performance during wet drilling and that of dry drilling. The drilling performance (rate of penetration and drilling torque) increased with improved cleaning, especially at increased WOB levels (where there is often the existence of higher disc cutter vibrations).

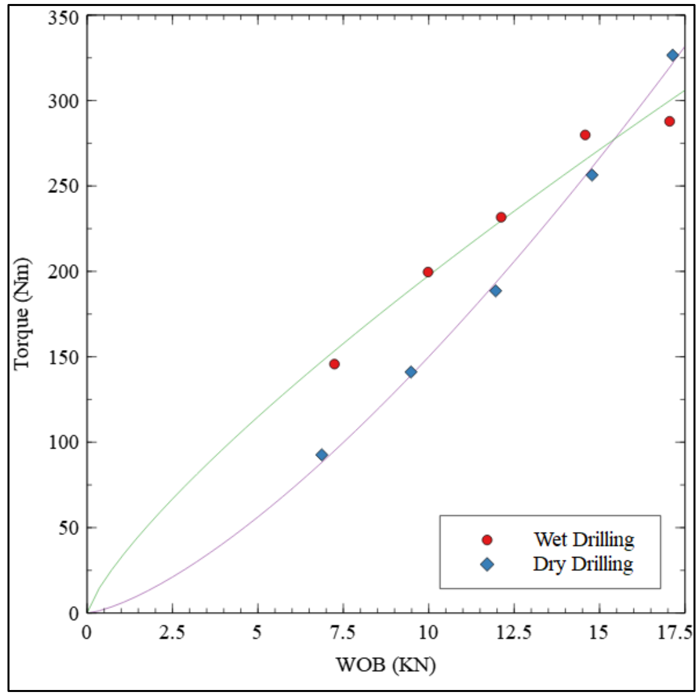

FIGURE 8: TORQUE VS WOB (WET DRILLING AND DRY DRILLING)

4. CONCLUSION

This technical paper has explored the impact of cleaning efficiency on drilling performance. The drilling system, rock properties, cutting tool features, different cleaning modes have been presented. The results of each set of drill-off test were analyzed.

These results show that there are observed relationships between the drilling performance and the adopted cleaning efficiency. For the same applied WOB and rotary speed, the drilling performance (rate of penetration and drilling torque) was higher for the wet drilling setup. This is an indication of better cuttings cleaning by the wet drilling method. This is completely in alignment with the expectation from literature. One key source that had been previously cited (Maurer, 1965) explains that for the same set of input WOB (at constant rotary speed), the drilling rate and drilling torque increase with perfect cleaning. Conversely, for poorer cleaning conditions, the drilling rate and drilling torque are expected to decline with increasing applied WOB.

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