Investigation of Hole Widening Drilling Using Cutting Analysis

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ABSTRACT
In narrow vein mining (NVM), mining excavation commonly transfers from open pit mining to drilling excavation based on the cost and efficiency. Mining drilling is generally conducted on the narrow vein, along with next-step excavation of hole widening drilling. In Drilling Technology Laboratory (DTL), the two stages of drilling methods are under study to assist in the NVM. Drill-off Tests (DOT) were conducted using a small drilling simulator (SDS) in laboratory. Drilling performance of pilot hole drilling and hole widening drilling were evaluated based on the following parameters: rate of penetration (ROP), torque, rotary speed. A well planned schedule was made to achieve this goal, in addition the cuttings were collected for further analysis. Cutting size analysis helps to correlate the drilling performance for varying drilling stages, i.e. pilot drilling and hole-widening drilling, and rock types. Cutting size analysis also correlates to other drilling responses such as torque, rotary speed based on the variation of previously stated parameters. A combination of cutting analysis, drilling response and drilling performance results in a detailed explanation of the hole widening drilling process. This will assist in drilling plan for hole widening operation for narrow vein mining.

ABSTRAIT
Dans les mines à filons étroits (NVM), l'excavation de mines passe généralement de l'exploitation à ciel ouvert à l'excavation de forage en fonction du coût et de l'efficacité. Le forage minier est généralement effectué sur la veine étroite, de même que l'excavation à l'étape suivante du forage d'élargissement du trou. Au Drilling Technology Laboratory (DTL), les méthodes de forage en deux étapes sont à l'étude pour faciliter la MNV. Les tests de forage (DOT) ont été réalisés à l'aide d'un petit simulateur de forage (SDS) en laboratoire. Les performances de forage pilote et d'élargissement de trou ont été évaluées en fonction des paramètres suivants: taux de pénétration (ROP), couple, vitesse de rotation. Un calendrier bien planifié a été établi pour atteindre cet objectif. De plus, les boutures ont été recueillies pour une analyse plus approfondie. L'analyse de la taille de coupe permet de corréler les performances de forage pour différentes étapes de forage, c'est-à-dire les forages pilotes et les forages pour élargir les trous, et les types de roches. L'analyse de la taille de coupe est également corrélée à d'autres réponses de forage, telles que le couple et la vitesse de rotation, en fonction de la variation des paramètres indiqués précédemment. Une combinaison d'analyse de coupe, de réponse de forage et de performance de forage donne une explication détaillée du processus de forage d'élargissement du trou. Cela facilitera le plan de forage pour l'opération d'élargissement de trous pour l'extraction de filons étroits.

1 INTRODUCTION

Rotary drilling is a conventional drilling method used to drill a well to produce oil or gas from the reservoir to surface. Rotary drilling involves i) applying axial force on the bit or Weight-on-Bit, ii) turning the bit to penetrate the formation and iii) flowing drilling fluid through the bit to flush the cutting and carry them to surface. (Lambert et al. 2005). These three parameters are generally called as bit operating conditions. During drilling operation, drilling fluid or mud is circulated down the drill string and through the bit nozzle in order to clean the bottom-hole from the generated cuttings. The rock cuttings are then lifted to the surface through the annular space between the borehole and the drillstring exterior.

Hole widening operation is basically done to enlarge small diameter pilot hole to a fixed diameter larger hole. Generally, hole openers are used to drill enlarged hole. These are usually run in the hole on top of the bit that makes it easy to remain in the center of the hole and to follow the previously drilled pilot hole. In lab scale, first a small diameter hole can be drilled and then it can be enlarged to larger diameter for analysis the hole widening operation.

Drilling performance of a well is the time taken to construct the wellbore. Most of the time the main goal for the operators is to accomplish high rate of penetration. The main parameter that drilling engineers consider as a performance investigative is the rate of penetration (ROP). Rate of Penetration (ROP) depends on axial downward force called as Weight on Bit (WOB). ROP changes with varying WOB and the relationship between ROP and WOB is not linear at all. From different lab experiments and field data it is found that ROP results as a function of WOB and rotary speed. Drilling performance can also be defined by three groups of parameters named as Rock characteristics, machine parameters and operating processes (Altindag, 2003). Different researchers worked earlier to establish a relationship between these three parameters and cutting analysis and one research concluded that the particle size of the cuttings become coarser as the ROP increases (Pfleider and Blake 1953).

Drill cuttings works as a very good source of information. Cutting analysis can be used to evaluate the penetration mechanisms by relating the size and shape of the cuttings to the fracturing mechanisms. (Reyes et al. 2015). According to Pfleider and Blake (1953), the size of the cuttings is strongly related to ROP and this ROP depends in RPM and WOB up to certain point. After the optimum point ROP starts to decrease as it begins to grind the particles and hole cleaning can not be done perfectly.

In the past, members of Drilling Technology Laboratory at Memorial University of Newfoundland have investigated the relationship between cutting sizes and shape with the drilling parameters to improve the drilling performance. This paper focuses on analysis cutting size that were generated in the laboratory during drilling pilot hole and hole widening experiments and its relation with drilling parameters such as Rate of Penetration (ROP), Weight on Bit (WOB), Revolution per Minute (RPM) etc.

2 EXPERIMENTAL EQUIPMENT AND PROCEDURE

For doing the investigation of pilot hole drilling and hole widening operation using cutting analysis several Drill off Tests (DOT) were conducted in the Drilling Technology Lab by ensuring proper cutting collection. A Small Drilling Simulator (SDS) was used to conduct the drill of tests.

2.1 Materials

A Granite block was used to perform the drill off test. The un-confined compressive strength (UCS) of the rock is about 175 MPa (Figure 1). The dimension of the granite block was 12 inch in length, 12 inch in width and 8 inch in height. A cutting collection system comprises of a thin walled sealed container, a pipe connecting the container with a bucket was attached with the granite block.

Figure 1. Granite Block used in DOT.

2.2 Drilling System

A small drilling simulator was used to drill the pilot hole and enlarged hole (Figure 2). Tap water of a constant flow rate is used to perform the drilling and cleaning of the hole. WOB is applied by the use of a mass suspended on a wheel. The rotation is provided by a rotating motor which can produce two different settings of rotary speed, 300 rpm and 600 rpm. 300 rpm is used in this lab experiment.

Figure 2. Small Drilling Simulator (left) and cutting collection system installed (right).

For pilot hole drilling two types of bit was used, coring bit of 26.4 mm diameter and PDC bit of 32.4 mm diameter. After drilling of the pilot hole section, PDC bit was used to enlarge the hole.

2.3 Overview of Cutting Size Analysis Procedure

After each run of drill off test, the cuttings were collected. It was ensured that the surface of the rock is sufficiently clear for the next run. ASTM standard D6913-04 (ASTM 2009) and cutting collection procedure from researchers of DTL (Reyes et al. 2015) was followed for proper collection of cuttings. After collection, cuttings were put in the oven for 12-14 hours and dried them at the temperature of 60-70 degree Celsius. After fully dried, the entire sample was sieved for analysis.

Different sizes of cuttings were sieved with mesh sizes of (Figure 3):

- 2 mm,
- 850 micron,
- 630 micron,
- 315 micron,
- 250 micron,
- 150 micron and
- 75 micron.

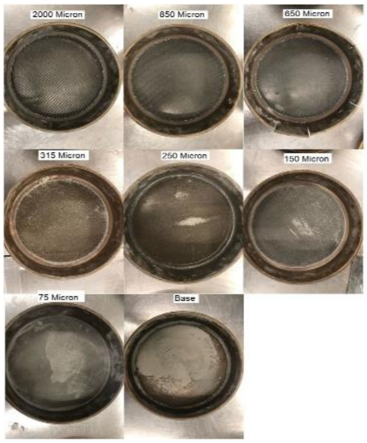


Figure 3. Different sieve sizes used for sieve analysis.

An automatic sieve shaker was used to separate different sizes and then the weight of the each sieve mass was measured for particle size analysis (Figure 4).

Figure 4. Oven and standard sieving machine used to sieve analysis.

3 RESULTS AND ANALYSIS

During each drilling, cuttings were collected and all the 12 cuttings samples generated by lab experiment, cumulative weight percentage of passing particles was calculated. Particle size distribution diagram (PSD) is a very convenient tool to show the distribution of cutting size. Different drilling parameters like penetration depth, bit vibration, duration, WOB of drill off tests were being automatically saved in the software. These data can be used for further analysis of drilling performance.

3.1 Drilling Performance Evaluation

By using small drilling simulator, drill-off tests were conducted and different drilling parameters were analyzed for the evaluation of drilling performance. Drill-off tests were conducted in the granite block with a rotary speed of 300 rpm. For different bits and different WOB, depth vs time graph and vibration vs time graphs were created (Figure 5). These graphs were then used to generate ROP and RPM for different configurations.

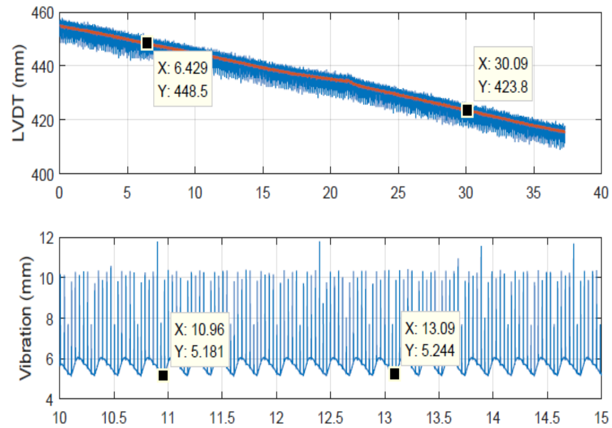


Figure 5. (a) Depth vs Time and (b) Vibration vs Time graphs from where ROP and RPM was calculated.

Four different types of WOB was applied on drill bit by the use of suspended mass from the wheel. These WOB were basically chosen by number of weight plates and these plates have different weights accordingly. The table 1 below shows the relation between numbers of plates with WOB in Kg.

Table 1. Number of plates and WOB relationship.

No of Plates	WOB(Kg)
1	108.4
3	135.4
5	164.8
8	212.4

Under laboratory conditions, applied WOB varied from 108.4 Kg to 212.4 Kg. For these 4 different WOB corresponding ROP was obtained for three different drilling conditions. First one is for pilot hole drilling using PDC bit, second one is for coring bit and third one is for enlarging the 26.4 mm drill hole to 32.4 mm hole using PDC bit (Figure 6).

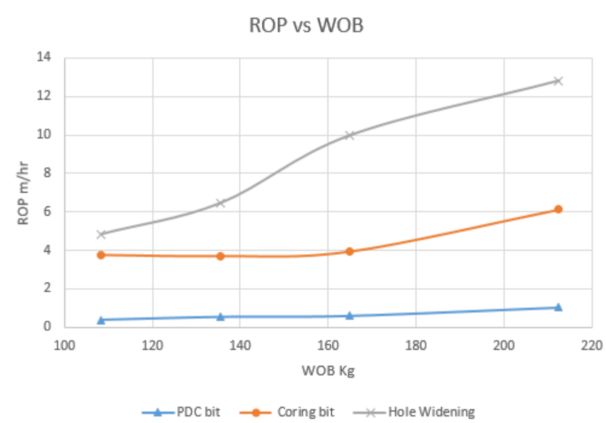


Figure 6. Rate of Penetration (ROP) vs WOB obtained from lab experiments for three different conditions.

From this figure it is shown that ROP increases with increasing WOB for each drilling condition. During lab experiment the RPM that was obtained was not the same as generated the motor of SDS. To eliminate the effect of rotary speed on penetration rate, both ROP and rotary speed was normalized to 300 rpm. Normalized ROP was got from the main ROP multiplied by the ratio of rated rotary speed oven the actual speed and the normalized rotary speed was obtained from the ratio of actual rotary speed over the rated one (Xiao et al. 2015). Figure 7 below shows the relation between normalized ROP and RPM with WOB. Here, RPM decreases with increasing WOB and for hole widening operation it is the lowest. It is because the pre-existing hole make the drilling with PDC bit more challenging with more energy required. Normalized ROP is greater than actual ROP for all drilling conditions because of deduction of rotary speed in normalized condition.

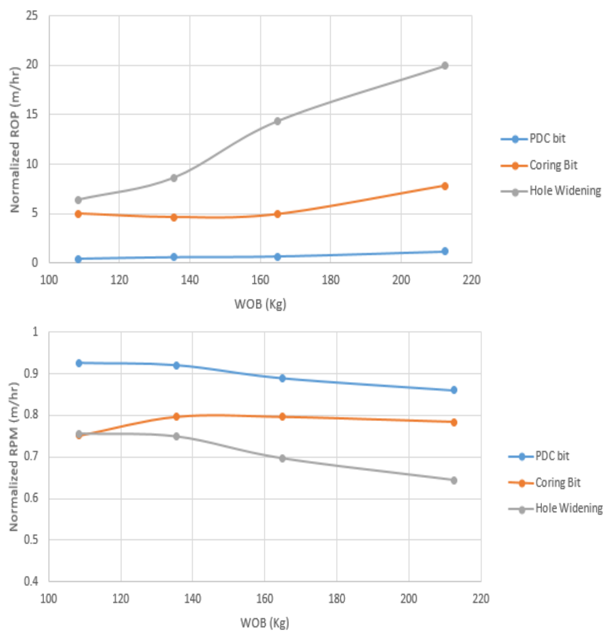


Figure 7. Graphs showing (a) normalized ROP and (b) normalized RPM as a function of WOB.

From figure 6 it is visible that ROP for PDC bit in pilot hole drilling is not very satisfactory whereas for hole widening drilling with same PDC bit it increased drastically. It is may be because of the fact that PDC is not a good bit to use in hard formation. The granite block that was used in the experiment has a UCS of 175 MPa and it is a hard rock. PDC does not show remarkable penetration rate in hard rock compared to soft formation.

In the other hand, same PDC bit showed noteworthy penetration rate in hole widening operation. This can be analyzed by Maurer's Perfect Cleaning Model (Maurer 1962). According to Maurer (1962), ROP varies directly with the RPM and the square of WOB. And varies inversely with the square of the bit diameter and the square of the strength of the rock being drilled. The equation is as follows:

$$ROP = \frac{K}{S^2} * \left(\frac{W - W_o}{D}\right)^2 * N \qquad [1]$$

where,

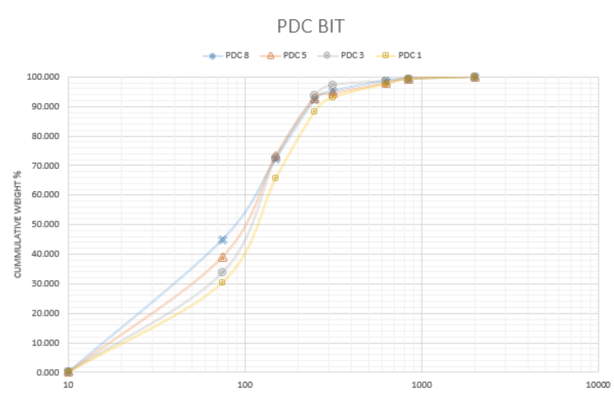
ROP: Rate of Penetration
K: Bit calibration constant
W: Weight on bit
W_o: Threshold weight on bit
D: Bit diameter
N: Rotary Speed
S: Strength of rock (UCS)

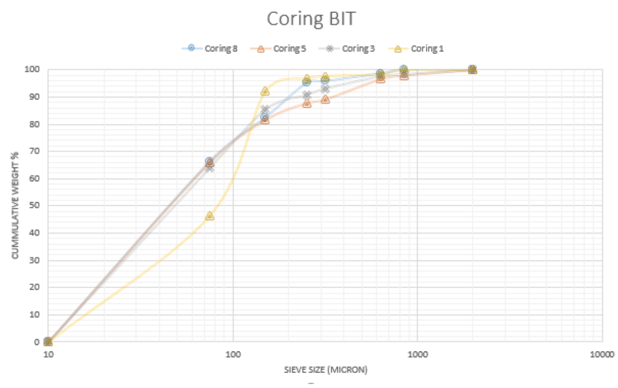
From Maurer's Model it is evident that ROP has a inverse relationship with the diameter of the hole which basically also represents the corresponding area of the hole. Hole widening is the process of enlarging a previously drilled hole to a new diameter bigger hole. As for the previously drilled hole, during hole widening operation, the area below the bit is so small compared to conventional drilling it has a great impact on ROP. ROP is inversely proportional to the square of the area of the drill hole. For this phenomenon, ROP in hole widening operation for PDC bit increased dramatically compared to pilot hole drilling.

3.2 Particle Size Analysis

Particle size distribution diagram (PSD) is a convenient method to display the cutting size distribution. In the diagram, Y axis is designated as cumulative weight percentage and X axis is for sieve size in micron. For a good distribution of the curve, the horizontal axis is plotted in logarithmic scale. If the cumulative percentage is lower for any selected sieve size, the higher percentage of the cuttings will be left in sieve.

Particle size distribution diagram (PSD) was obtained for three different drilling conditions. As mentioned above one is for Pilot hole drilling with PDC bit, one is for Coring bit and last one is for hole widening operation using PDC bit. Size of the cuttings ranges from 10 micron to 2 mm. Figure 8 show the PSD for different drilling conditions.





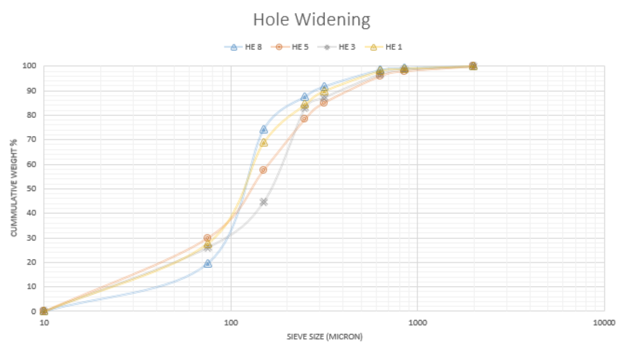


Figure 8. Particle size distribution (PSD) diagram for three different drilling operations, (a) PDC Bit, (b) Coring Bit, (c) Hole widening operation

From figure 8c, for hole widening operation with PDC it cutting size is bigger for higher WOB. For 212.4 kg WOB cutting size is coarser up to 100 micron range but for 164.8 kg WOB cutting size begins to become larger than others as it is moving to the right size. It may be because of for higher WOB of 212.4 kg the particles began to grind more and 164.8 kg WOB worked as the optimum weight for perfect crushing and hole cleaning. In general, cutting size is coarser for higher WOB.

Coring bit did not show proper result for cutting size distribution but for PDC bit used in pilot hole drilling it followed a reverse trend (Fig 8a, 8b). Here, less WOB produced coarser particles. It may be because of hard rock. As PDC bit is not convenient for drilling in hard rock formation like Granite block with 175 MPa UCS.

Coarseness Index (CI) is another parameter to describe the size of the hole sample. It's a non-dimensional number that can be obtained by summation of cumulative weight percentages of a particular size (Altindag 2003). CI can be used to represent the size of the samples if same sieves are used for all the sampling. By using the CI, overall sample can be characterised by one number but it does not provide very good information about the sample size.

For 12 samples that were generated in the lab experiment with varying WOB, CI is calculated. Table 2 below show the CI for different samples. From this table it is shown that coring bit produces coarser particles than other two bits and hole widening operation using PDC produced overall finer size particles.

Table 2 CI for 12 different samples

WOB Kg	108.4	135.4	164.8	212.4
CI for PDC Bit	574.21875	595.0704	596.648	602.8939
CI for Coring Bit	631.496063	629.771	619.0476	638.4615
CI for Hole Widening	567.9612	536.5297	545.2736	571.1779

There is also a relationship between CI and ROP. The general trend is CI increases as ROP increases. But in these lab experiments this relationship was not found quite satisfactory for coring bit and hole widening operation. Figure 9 shows the relation between ROP and CI for PDC bit in pilot hole drilling.

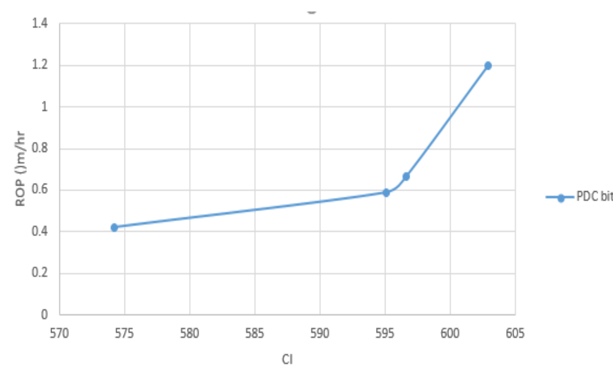
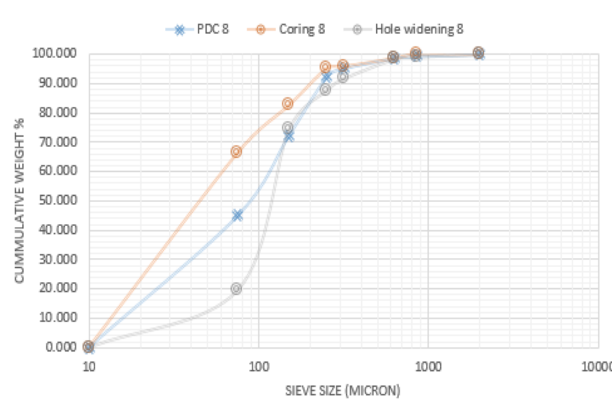


Figure 9. CI increases as ROP increases for PDC bit for pilot hole drilling

3.3 Particle Size Distribution for Different Bits

Particle size distribution is also investigated under different bits but same WOB. In different drilling conditions, with same WOB particle size distribution changes. It is found that for all hole widening operation the particle size is bigger relative to other pilot hole drilling. Figure 10 show the graphs representing the particle size relationship with different drilling settings.



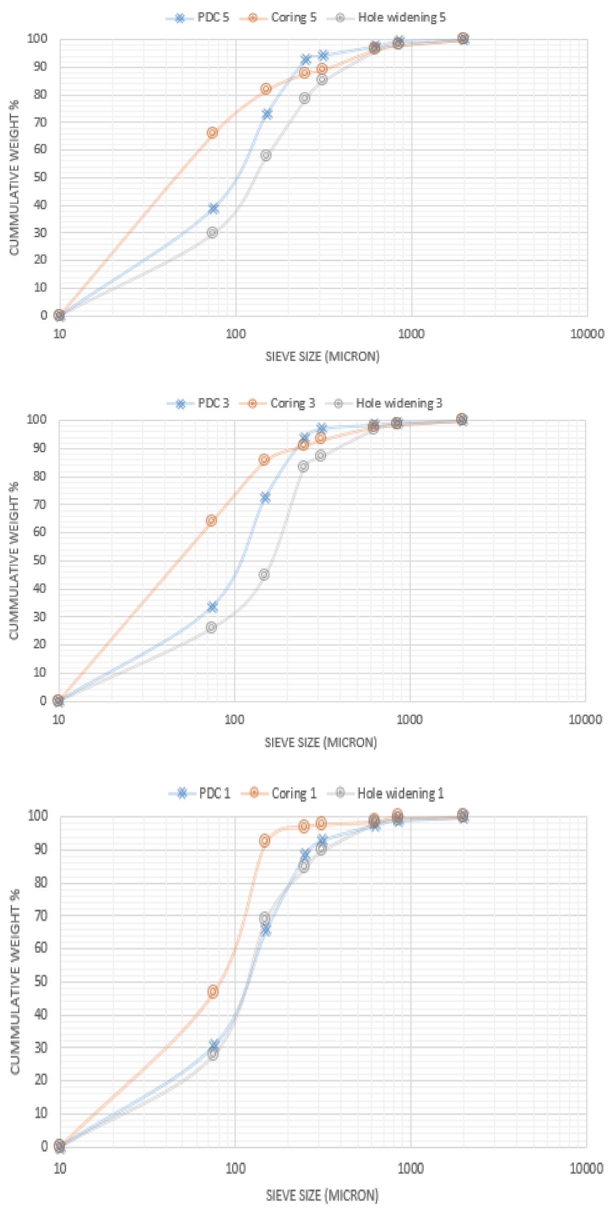


Figure 10. Particle size distribution for different WOB and drilling settings.

From the figure 10, it is evident that, for higher WOB hole widening drilling generate bigger particles and coring bit produces the finer ones. For less WOB of 108.4 Kg, PDC bit for pilot hole and hole widening drilling generate similar size of cuttings. This trend indicates that higher WOB has a tendency to generate bigger particle sizes for hole widening drilling as it does for other conventional drilling.

4 CONCLUSIONS

Results obtained from lab experiments and analysis, following conclusions can be made:

- Rate of Penetration (ROP) increases with increasing WOB for all drilling conditions.
- For hole widening operation a strong relation has been found with Maurer's perfect cleaning model (Maurer 1962). As the area of the contact surface of the hole penetrated by the bit decreases the Rate of Penetration increases dramatically.
- Particle Size Distribution (PSD) diagram is a useful instrument to represent cutting size for different samples.
- Coarseness Index is found not to be a good indicator of the particle sizes. It does not work perfectly for all the drilling settings. It may be works as a rough estimator of the cutting size.
- Hole cleaning is an important issue for proper cutting collection and for getting good drilling parameters.
- Under the same WOB condition hole widening drilling produces coarser particles.

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