HOLE WIDENING DRILLING PENETRATION MECHANISM AND PERFORMANCE EVALUATION IN HARD ROCK UTILIZING CUTTING ANALYSIS.

by
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Abstract

Mining by drilling technique, a revolutionary breakthrough which has already created a wind of change in the industry of ore excavation. Mineral production form the narrow veins is a matter of great challenge and mining by drilling technique is providing the unique solution for this type of excavation. Large diameter hole drilling is performed for accomplishment of excavation from narrow vein ore bodies. Conventional rotary drill rigs are used to drill a small pilot hole through the center of the vein and then the large diameter hole is drilled on the same hole where pilot bit works as a guide or stabilizer for large diameter bit. Pilot hole are drilled to understand the geology, geometry of the formation and the large diameter hole drilling works as the main production process of the ore.

Lab based Drill-Off Tests were conducted to evaluate the pilot hole drilling and hole widening drilling process. Drill cuttings were used as the main source of information and shape, size, volume of the particles were examined carefully for proper assessment of the drilling process. Performance of these two types of drilling process were estimated based on Rate of Penetration (ROP), Revolution Per Minute (RPM), Mechanical Specific Energy (MSE) and Drilling Efficiency (DE). Relationship between drill cuttings particle size parameters and drilling parameters were investigated for proper appraisal of hole widening drilling process. A detailed study was performed to assist field scale hole widening drilling operations that involves intensive analysis of cuttings, drilling parameters, and drilling performance.

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List of Nomenclature

CCS	Confined Compressive Strength
CI	Coarseness Index
D_B	Bit Diameter
DE	Drilling Efficiency
DOC	Depth of Cut
DOT	Drill-Off Test
HWD	Hole Widening Drilling
LDS	Large Drilling Simulator
MSE	Mechanical Specific Energy
N	Rotary Speed
NVM	Narrow Vein Mining
PDC	Polycrystalline Diamond Compact
PSD	Particle Size Distribution
ROP	Rate of Penetration
RPM	Revolution Per Minute
S	Rock Strength

SE	Specific Energy
SDS	Small Drilling Simulator
TOB	Torque on Bit
UCS	Uniaxial Compressive Strength
WOB	Weight on Bit
WOR	Weight on Reamer
μ	Bit Specific Coefficient

Chapter 1: Introduction

This introductory chapter outlines the process of narrow ore body mining using conventional drilling technique used in petroleum industry. The section discusses the challenges associated with extracting ore from narrow veins and how conventional drilling technique can provide a solution to this problem. The research objective and thesis outline are also presented, providing an overview of the study.

1.1 Background of the research

In today's world, the demand for different forms of minerals is increasing, heightening the requirement for modern methods of exploitation. All the exploration and production companies, whether from oil and gas or mining industry, are running faster to cope with increased demand, while at the same time attempting to mitigate the cost of production for end use. Several research studies have experienced difficulty in evaluating the feasibility of exploration, exploitation and production methods in terms of their economic burden and environmental cost. In the oil and gas industry, operations have become more inaccessible and challenging, the target depths for the wells are evolving as impressive and reservoir geometry is becoming technically trickier. All of this requires new and innovative techniques to extract resources.

On the same note, the mining industry also requires more innovative technologies and novel ideas for the extraction of minerals that cannot be achieved through regular mining processes. Various types of minerals are available in Canada, and specifically in Newfoundland and Labrador, that cannot be exploited by conventional mining methods like open pit or underground mining. Narrow vein deposits are very challenging to exploit as they offer very complex geological geometry. Narrow veins are defined as those veins for whom the width ranges from less than 3 meter to 6 meters [1]. It is very difficult to estimate the reserve of the narrow veins and to select the appropriate method of effective exploitation because of the variation in vein geometry as well as grade distribution [2].

From the context of conventional mining methods, operators found it very difficult to mine narrow veins economically and efficiently as they do not offer proper orientation for any types of surface mining. Further, it becomes more challenging to develop underground mining process as it requires extensive infrastructure development to mine the veins. In the Drilling Technology Laboratory (DTL) at Memorial University of Newfoundland, researchers have undertaken a study to develop a method to extract valuable mineral resources from the narrow veins by utilizing the conventional technique of drilling engineering that is used widely in oil and gas industry. In this method, mining of the veins can be commenced using drilling engineering concept where a small diameter hole is drilled first through the center of the vein between the hanging wall and the footwall. This hole is referred to as pilot hole. Hole opening tools are subsequently used to ream the larger diameter hole following the path of the pilot hole to allow extraction of the whole ore body [3]. Reverse circulation (RC) drilling technique is proposed to be used in the operation by which ore from the ore body will be recovered as drill cuttings through the drill string. This will eliminate the use of explosives and also prevent grinding or crushing of the ore [4].

Several researchers have been working for the last 50 years to assess drilling performance on the basis of size, shape, and mineralogical description of the drill cuttings. In a drilling engineering study, a close correlation between the drilling mechanisms, drilling conditions and particle size distribution (PSD) of the drill cuttings has already been confirmed [5]. Particle size distribution has been used to characterize penetration mechanism, bit-rock interaction and drilling performance [6]. Drill cuttings size also has an impact on the energy utilized by any drilling operation. The generation of drill cuttings with smaller sizes of particles during drilling is more energy expensive as it produces higher specific surface area [7].

1.2 Research Objectives

The purpose of this study can be outlined as below.

- Evaluating the hole widening operation and assessing the hole widening technology to get clearer insights into the large diameter drilling process to assist a new innovative drilling technology.
- Performance evaluation of hole widening drilling by means of understanding the relationship between drill cuttings data like particle size distribution (PSD) with various drilling parameters such as Rate of Penetration (ROP), Weight on Bit (WOB), Rotary Speed, Mechanical Specific Energy (MSE) and Drilling Efficiency (DE). In the past, these types of relationship have been evaluated for blind hole drilling or pilot hole drilling method. This study more focuses on hole widening drilling evaluation by comparing with pilot hole drilling.
- Design and implementation of a cutting collection system for the Large Drilling Simulator (LDS) and the Small Drilling Simulator (SDS) of the Drilling

Technology Laboratory (DTL) based on experimental results to support future drilling experiments and analysis of drill cuttings.

1.3 Thesis outline

Chapter 2 gives an overview of the rotary drilling process, the hole widening operation, the drill cuttings size analysis and performance evaluation of a hole widening drilling operation. It describes different methods of particle size analysis and presentation of the particle size distribution. It talks about the relationship between drilling performance and particle size, as summarized by different researchers in previous studies.

This chapter also includes information about large diameter hole drilling techniques and, types of additives that are widely used in the industry to improve the drilling performance. This information can provide an improved understanding about how to make large diameter drilling operations more efficient and economically viable.

Chapter 3 describes the analysis of particle size generated by lab experiments and the relation of particle size with various drilling parameters. It includes the design and implementation of a cutting collection system for a Small Drilling Simulator (SDS) and the process of generating cutting size distribution data for analysis. A complete procedure of the hole widening drilling operation in lab scale is presented in this chapter.

Chapter 4 includes a comprehensive study that can be used to provide recommendations for field scale hole widening operations. This chapter gives insight into drilling performance evaluation for hole widening drilling by involving intensive analysis of drill cuttings size, and drilling input and output parameters like ROP, RPM, WOB, MSE and

DE. It also describes the mechanisms of the hole widening drilling process in comparison to pilot hole drilling.

Chapter 5 describes a design and implementation procedure for cutting collection systems for the Small Drilling Simulator and the Large Drilling Simulator. This cutting collection system has been installed in the Drilling Technology Laboratory (DTL) at Memorial University of Newfoundland to collect the cuttings generated by different Drill-Off Tests (DOTs) and other experiments. This chapter shows various data from drill cuttings generated by different stages of drilling operations like the pilot hole and hole widening drilling stages. It also illustrates how these data were used to design a proper and cost-effective cutting collection system.

Chapter 6 summarizes all the outcomes of this study, indicating the contribution of this research to mining by drilling method and provides recommendations for the future works.

Chapter 02: Literature Review and Methodology

2.1 Basic components and Mechanism of Rotary Drilling

Modern civilization has recognized hydrocarbon fuel as a livelihood to the society and a vital component to lead the whole humankind. The extraction and exploitation of petroleum hydrocarbons includes the process known as drilling, the technique which was developed through a lot of researches and studies by professionals. Drilling engineering is a branch of engineering that studies the drilling of wells through the earth's crust to produce oil and gas in a sustainable manner and with the most cost-effective method.

From history, it is evident that oil well drilling activities were performed in C.E. (Common Era) 347 in china and C.E. 600 in Japan as well [8]. In the modern era, percussion drilling had been widely used as a drilling technique until the 1930s and after that rotary drilling started to evolve as the best technique to utilize in deep drilling. The rotary drilling technique involves the rotation of a drill bit connected to a drill string or BHA to cut the rock formation in a forward moving direction [9].

Different types of wells are drilled to fulfill different purposes. Exploration wells are drilled to explore a reservoir, and after the exploration phase development wells are drilled for production from the reservoir. Injection wells for special purposes are also drilled for different objectives during the life of a reservoir. To drill a well whether it is for appraisal purpose or for production, other aspects such as drilling fluid, casing, cementing, directional drilling tools, perforating operations, drill bits, drill pipes, and well logging are also needed to accomplish the job with proper accuracy and efficiency.

The rotary drilling technique involves i) axial force on the drill bit, ii) rotation of the drill bit to penetrate through formation, and iii) fluid or mud flow through the drill bit to the annulus to carry the cuttings to the surface [10]. These actions require power and energy that need to be provided to the drill rig system, and six basic components the power system, hoisting system, rotary system, circulating system, well control system and well monitoring system serve these purposes.

The rig power system provides sufficient energy and power to the equipment that requires high mechanical, hydraulic and electric power to operate. These include drawworks, mud pumps, rotary system, and other support systems. Hoisting system and fluid circulation system consume most of the power generated by power system.

The vertical movement of the drill string or BHA is generally provided by the hoisting system. It allows the raising of the travelling block and adding or removing of drill pipes (called as making a connection or making a trip) that needs for continuation of the drilling operation.

As drilling progresses, it generates a lot of cuttings because of the action of the drill bit. To ensure better drilling performance, the cutting must be removed from the downhole and pumped to the surface. This process is handled by the mud circulation system. The mud circulation system provides the hydraulic power that is needed to pump the mud along with the cuttings to the surface through the annulus. The mud pump, mud pit, mud mixing equipment and contaminant removal system are the main components of the circulation system.

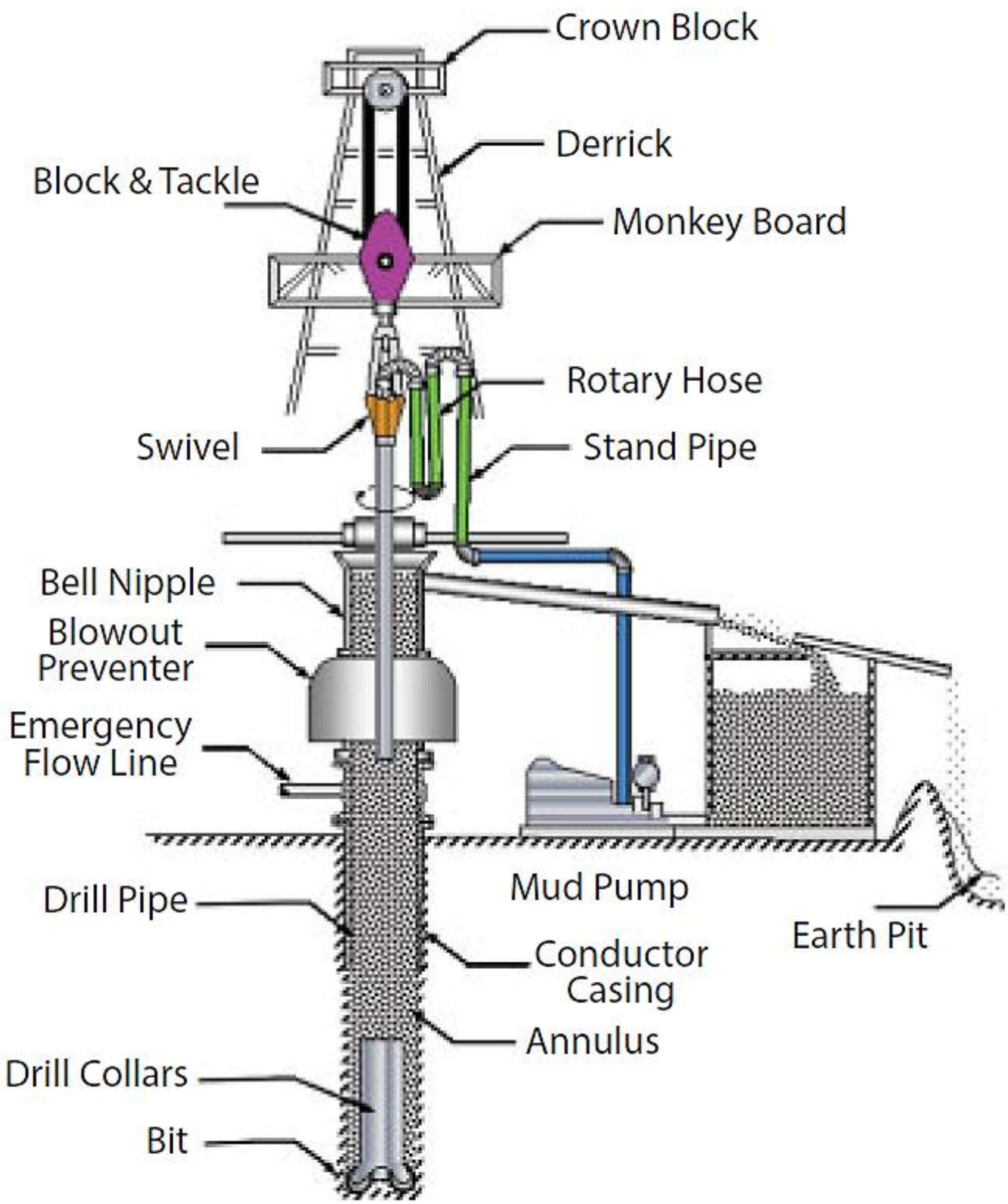


Figure 1: A conventional rotary drilling rig showing all the basic components [9]

As a basic requirement, drill bit rotation is achieved by the influence of the rotary system. This comprises all the equipment used to attain bit rotation in the downhole. Rig based and downhole based rotary systems are the two basic types used in the operation. The rig based rotary system includes the rotary table, the kelly system, and the top drives. The downhole rotary system includes the positive displacement mud motor (PDMM) and the turbodrill [10]. The Bore hole assembly or BHA, includes the drill pipe, drill collar, and stabilizer to transfer the power to the bit for axial and torsional force generation.

To ensure safer drilling operations, a well control system is a must. The uncontrolled flow of formation fluid to the well bore during drilling is identified as a kick, and well control system always works to detect the kick and prevent blowout. The well control system enables drilling personnel to detect the kick and close the well at the surface. This helps to keep circulation of the well by increasing mud density and well bore pressure, and while the well is closed, it keeps the movement of the drill string and diverts the flow away for the drill rig.

The well monitoring systems are used to check, record, and evaluate different drilling parameters in real time operation. Some parameters cannot be detected automatically but for safety these are monitored constantly by the operators.

2.2 Large Diameter hole drilling and Hole opening Technology

Large diameter holes had begun to be drilled in late 1950's to improve production rate and from 1953 to 1967 big holes hit the footage of 5000 ft to 117000 ft with a hole of 36 inches in diameter [11]. James H concluded in his study that proper hole cleaning with sufficient mud circulation was a big challenge at that period as the industry drilled a 90-inch diameter single pass hole for uranium mine ventilation shaft using large bore special tools [12]. Lackey (1983) from field experiment results stated that at the Nevada test site, big hole drilling was performed in 1961 where 450 holes with at least 48 inch in diameter and 500 ft deep. These operations were performed using large oil field type drill rigs with minor modifications [13].

Anglo-Gold-Ashanti in 2015 reported in their yearly published report, “Planning for the Future” that in Tautona mine site, 30 holes were drilled at diameters of between 660mm and 720mm. This drilling method required a double-pass drilling sequence where an initial pilot or direction hole is drilled, followed by a larger diameter cutter that reams the initial hole to a greater width [14].

In 1968 a project with raise boring program was initiated in South Africa where large diameter hole of 2100 mm were drilled using pilot hole of 280 mm in diameter and achieved 0.61 m/hr penetration rate with longer life expectancy for cutting rings and bearings [15].

For any hole opening drilling operation first a smaller diameter pilot hole is drilled to serve as a steer to follow for straighter wide hole [12]. Hole opening drilling was first introduced to drill a larger diameter hole following a small diameter pilot hole. The exercise of hole opening technology has evolved from an optional use to common practice for most drilling operations. In the early stage of hole opening technology development, hole enlarging operations were performed separately after pilot hole drilling which reduced overall rate of penetration. A bull nose was used to guide the hole opener and stabilizers to centralize the tool through the pilot hole while using hole enlarging apparatus. According to Mefford R. N. (1965), proper design of hole openers and underreamers are prerequisite to solve the problems generated by hard abrasive formations and produce a longer continuous run in the hole [16].

When the required diameter for the pilot hole for hole opening drilling cannot be achieved, pilot holes can be reamed to large diameter holes by using large diameter drill bits in the single pass method. In these cases, proper borehole assembly (BHA) is used to drill large diameter holes as straight as small pilot holes [12].

Bi-center bits were introduced to industry and were later developed as symmetrical underreaming while drilling tool. Numerous improvements were evaluated by using the symmetrical underreamer tool over bi-center bit such as directional control, longer run in the borehole, better wellbore quality, and increase in ROP. As the symmetrical underreamer equally distributed the load on the full size bit this resulted in higher ROP [17]. There are a lot of advantages of using hole opening technology such as:

- Small rigs can be used to drill larger diameter holes.
- It provides straighter holes.
- Cutters can be replaced for efficiency.
- Hole openers can be made for any size of the holes and for any formations.
- Large diameter rock bits are more expensive relative to hole openers.

Figure 2: Hole opener of 114.3 mm diameter used in experiments at the Drilling Technology Laboratory (DTL)

Hole enlarging while drilling has been evolved as a tremendous technique to drill interbedded formations in deep water and onshore drilling projects. D.R. Algu (2008) concludes that optimum designing of the cutting structure of the reamer and WOB (Weight on Bit) by WOR (Weight on Reamer) ratio result in significant improvements in drilling performance and wellbore stability [18].

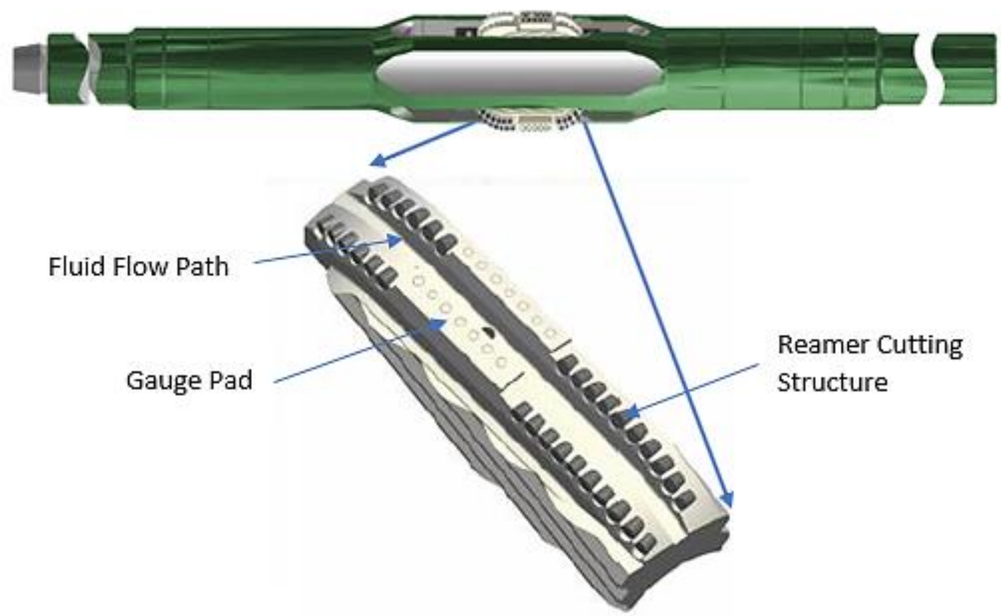


Figure 3: Concentric reamer and reamer cutter block used in hole enlarging operations [19]

The underreamer might face severe problems in formations with higher UCS and plastic behavior which require higher WOB and torque that inversely affect ROP. By balancing the bit and reamer cutting structure these types of problems can be mitigated in some extents [20].

Raise boring is another method that is utilized for drilling a bigger hole. It was developed to meet the demands of the mining industry, tunneling and also for constructing big infrastructure on earth. The principle of raise boring is the same as hole opening drilling where a small diameter hole is drilled first and then reaming is performed to drill the hole to the desired size. This technique is generally employed when holes are ranges from 0.6 to 6 m diameter and up to 1000 m in depth [21].

Cutters are used to excavate rock when reaming or boxhole boring upward, or shaft sinking downward. These are mounted on cutter housings positioned and fixed to the reamer and are designed to be the expendable wear item of the raise boring operation. Hence, they are removable and can be replaced in the field. There are at least four types of cutter geometry used for large hole drilling applications. These are:

- Disc cutters,
- Kerf carbide insert cutters,
- Rowed cutters and
- Randomly placed carbide insert cutters.

Figure 4: Four types of cutter used in large hole drilling operations [21]

Selection of cutters is a critical part of any project and it depends on several issues especially size of the cutter, rotational speed of the cutters, geology of the formation, abrasivity of rocks are main subjects to look at. Uniform distribution of the cutters will minimize the variation of the eccentric forces and out-of-axis moments [22].

2.3 Rotary Drill Bits

To break the rock, drill bits work as the key tool by conducting the drilling actions via scrapping, chipping, gouging or grinding the rock. Two classes of bits are widely used as the lead component of the drill string to grind the rock formation during drilling; i) Roller Cone Bit and ii) Fixed -cutter bit. Before the 1930s, in shallow wells drilling, fixed cutter bits were used but when the industry needed to drill deeper into hard formations, the tri-cone or roller cone bit was introduced [23].

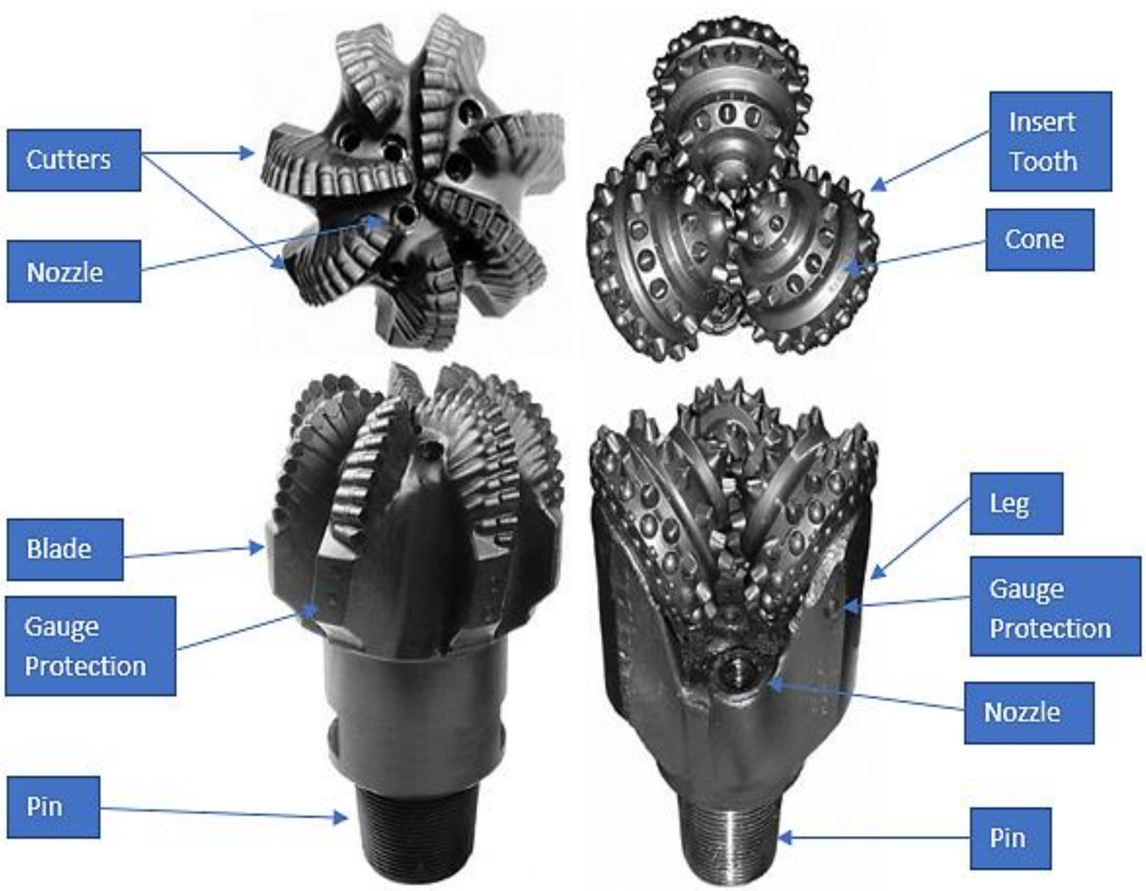


Figure 5: Conventional Fixed-cutter bit and Roller cone bit

Roller cone bits generally have three interlocking cones with cutting elements, like carbide insert tooth or milled tooth depending on the hardness of the formation. The cone offset determines the drilling action of the rolling cutter bits. When designing the roller cone bits, the cone is placed in such a way that the axis of the cones does not intersect in a common point at the center of the hole. The degree of cone offset is described as the parallel distance among the axis of the bit and a vertical plane through the journal axis [24]. Journal angle also control the cutting pattern as the bit drills through the rock formation and it effects the amount of cutter action at the bottom of the hole. The journal angle is defined as the angle formed by a line perpendicular to the axis of the journal and the axis of the bit [24]. The smaller the journal angle the greater the gouging and scraping action.

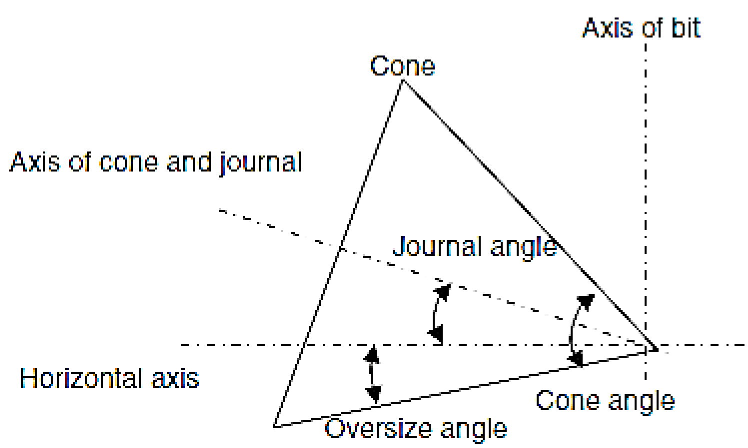


Figure 6: Journal Angle [25]

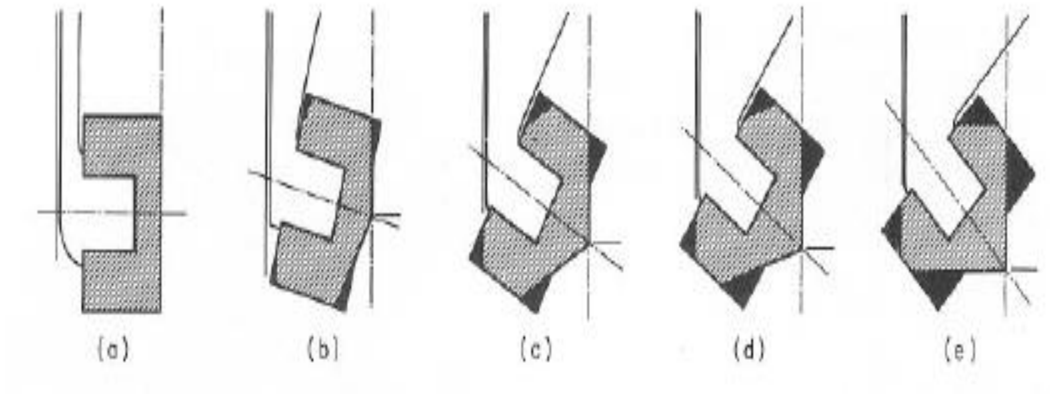


Figure 7: Influence of journal angle on cone size: (a) 0° journal; (b) 15° journal; (c) 30° journal; (d) 36° journal; (e) 45° Journal. Solid shading represents sections removed [24].

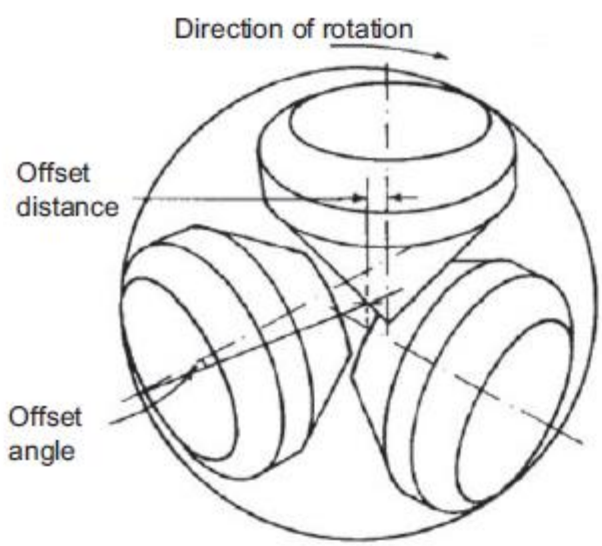


Figure 8: Cone offset of a tri-cone bit [25].

Fixed cutter bits do not have any moving parts and break the rock by two methods of action. PDC bits break the rock through a shearing process and impregnated bits made up of natural diamond and TSP elements, cut the rock through the grinding process. Design of a

PDC bit involves the number of cutters used and the angle of attack. Different designs involve different cutter exposures, and related siderake and backrake angles. Backrake angle is the angle of the cutter face to the horizontal plane of the rock formation and siderake angle measures the angle of the cutter face to the radial direction.

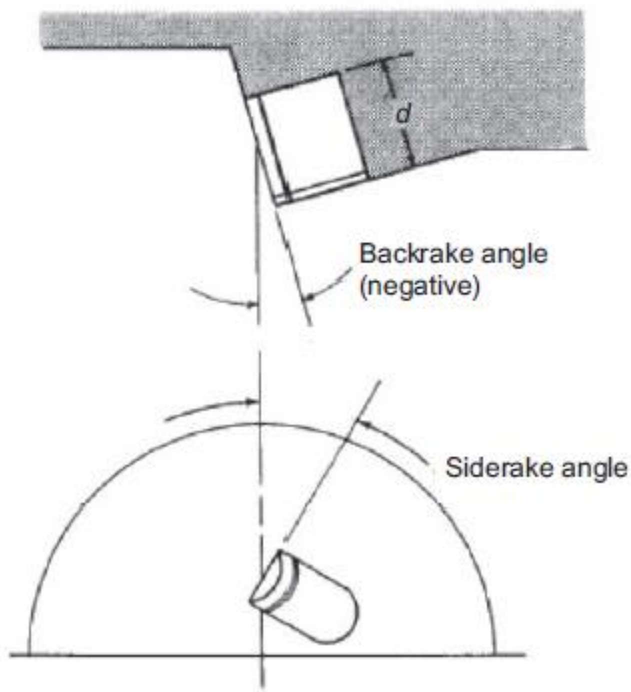


Figure 9: Orientation of the PDC bit cutter expressed in terms of backrake and siderake angle [25].

2.4 Drilling Fluid Additives for Improving Drilling Performance

Drilling fluid can be defined as the fluid comprising of different liquids and additives that is used to generated and remove the cuttings from the borehole beneath the bit face. Researchers have summarized the functions of the drilling fluids as : i) carry cuttings from the borehole to the surface and help to separate at the surface, ii) lubrication and cooling the bit, iii) reduce friction of the drill string in the hole, iv) provide borehole stability, v) prevent kick of formation fluid, vi) formation of a thin permeable filter cake to seal the cavities generated by bit, and vii) provide information about formation and lithology [26,27,28].

In general, the drilling fluids that are used in the oil and gas industry can be classified in to three major categories: i) Water Based Mud (WBM), ii) Oil Based Mud (OBM) and iii) Gas Based Mud [28]. Most of the drilling operations in the world are performed using water-based mud and approximately 5-10% drilling operations are done with the oil based mud [29].

Brantly (1961) reported that the water based mud was used as the first drilling fluid in any type of drilling operations and this water based mud can contain additives such as alkalis, salts, surfactants, organic polymers, and weighing materials like barite and clay [30]. Some major limitations of water based mud were concluded by Mellot in 2008 as: salts in WBM may dissolve and increase the density, interference of WBM with the flow of oil and gas through porous media, create dispersion of clay materials and develop corrosion in drill string. But there are also advantages of using WBM. WBM is cheaper, environment friendly, can enhance ROP and widely available in the market [31].

Oil based mud is highly preferable when drilling formations with high geothermal gradient which contains oil as the main part and water as the secondary part of the drilling fluid. OBM is basically used to mitigate the limitations imposed by WBM and also it can provide better lubrication and contain higher boiling point to survive better in high temperature zones [28].

In the current industry trend, it is now obvious to develop drilling fluids that has low toxicity, better efficiency, more environment friendly and of low cost. Many researchers have been working to formulate new improved drilling fluids with different additives. Microsized spherical polymers introduced by eco-friendly polymers form tamarind gum, amphoteric cellulose ether (ACE), Aluminum Hydroxide Complex (AHC) are some of those additives. Nanoparticles like nano-silica, nano-graphene and other nano based materials have also been used in experiments in the tenure of development of alternative mud additives. Oscar Contreras (2014) studied the effect of nanoparticles (NP) as additives in OBM. The experiment involved two different kinds of NP additives were tested NP1 (Iron based) and NP2 (Calcium based). The results showed that it was possible to increase the wellbore stability by preparing in-situ NP in the OBM [32].

It was found from the study that improved mud quality can alter rate of penetration by decreasing friction, increasing hole cleaning etc. Study conducted by Nasiri (2018) on monoethnolamine (MEA) and he found that it can be used with WBM to improve thermal stability of starch and prevents the destruction of starch at higher temperature. It was also found from their study that by using 1% to 2% of MEA concentration, the fluid can enhance drilling fluid's rheological parameters, can reduce the filtration rate of the fluids and increase the thickness of the mud cake [33]. From the experimental study of Krishnan et. al. that was published in 2016, it was observed that the ROP was increased from 3 m/hr to 9 m/hr by using Borate ester-based nanomaterial enhanced WBM additive also known as PQCB [34].

F.J Schuh in 2014 formed a technique that encapsulates biodegradable extreme pressure liquid lubricants in polysaccharide capsules. They performed a field trial by using encapsulated oil in a water-based mud containing Xanthum gum, starch, PAC LV, soda ash, glutaraldehyde and caustic soda. From the analysis, a better performance was attained in terms of ROP and in average ROP was enhanced by 216% [35]. From the study of other researchers, it was noticed that ROP enhancers like a mixture of long chain paraffins, a mixture of water-insoluble poly or PPG can result with better performance and drilling efficiency [36]. Zirconium citrate (ZrC) is another ROP enhancer that was used as additive in drilling experiments of Burrafato in 1997 [37].

Oil Based Mud (OBM) has been using in oil and gas industry to avoid instability of the borehole. OBM can prevent hydration and increase of pore-pressure as they contain emulsifier. Simpson in 1995, concluded in his research that, combination of hydroxyl groups with water soluble organic monomer on methyl glucoside provide a mud composition can prevent hydration and provide borehole stability [38].

2.5 Drill Cutting Analysis and Performance Evaluation

Drill cuttings work as a valuable source of information during drilling operations. Drilling mud or drilling fluid passes through the drill string and bit nozzle to the bottom hole to cool and lubricate the BHA, provides fluid pressure higher than the pore pressure to maintain the wellbore stability, and lifts the cuttings to the surface through the annulus [27]. Cuttings generated from different depths during drilling provide information about geology, geochemistry, stratigraphy, possible indications for hydrocarbon zone and other important data that cannot be gathered from downhole measurements as cuttings are the original rock sample of the subsurface [39].

Form a drilling engineering perspective, cuttings analysis provides real time information beneath the bit, and by proper measurement, interpretation of these cuttings can help minimize drilling problems and improve drilling performance. Form investigation of the cuttings, returning rate of the drill cuttings, shape and size of the cuttings, decisions can be made regarding proper hole cleaning and penetration mechanisms as these phenomena are the result of bit, rock and fluid interaction [40].

2.5.1 Particle size Analysis

Particle size analysis is performed to generate quantitative data about the size of the particles and distribution of the particle size. Drill cuttings produced during drilling operations contain particles of various size range. Particle size distribution can characterize the drill cuttings samples and relate with drilling parameters. Researchers from all over the world have established a relationship between drilling parameters and particle size percentiles.

In the industry and research laboratories, different methods and instruments have been used to do particle size distribution. Different methods are used based on the condition of the samples (dry or wet) and the size range of the samples. Selection of the proper method for particle size distribution can be performed by understanding the fineness of the particles and suspension media of the particles. Several methods of particle size analysis and presentation of particle size have been described in this study - for better understanding.

2.5.2 Sieve analysis

Sieve analysis or test sieving is a common and widely used method for particle size analysis. Both dry and wet particle samples can be tested by this popular method. It is considered to be one the oldest methods where particles are passed through different sizes of sieve or metallic meshes that are placed according to the fineness of the pore spaces, and the weight of each sieve is measured for further generation of the particle size distribution. In the test sieving method, particles of 75 microns or bigger are commonly sieved for analysis. Horizontal and vertical movements are imposed on the particles for proper sieving and the effectiveness of sieving to some extent also depends on the mass of the sample put on the sieve for testing.

Sieve analysis can be performed either by mechanical vibration or by hand. Almost all the tests are done by generating mechanical vibration by using a sieve machine as it is faster and easier than the hand sieving technique. Based on the size range of the particle, sieves are chosen to perform the test and arranged in stacks with the finest sieve at the bottom following coarser ones at the top. A sieve shaker is used to shake the sieves and making layers of various sizing particles on each sieve.

As the coarsest sieve is placed at the top, all the materials to be tested are put on it. The sieve shaker creates vibrations in the horizontal and vertical axis and undersize material falls through successive sieves. Particles then can be separated from each sieve as these are slightly bigger than their containing sieve mesh size [41].

The wet sieving technique is used when the sample materials are already in slurry or drying is not possible as they may flocculate or aggregate after drying. In the field, wet sieving can be performed by connecting the sieve shaker to a circulation system which will feed the shaker with the mud slurry. In this process, similar to the dry sieving process, cuttings are put on the top coarsest sieve by using a pump, and water is collected form the beneath the lowest sieve by a discharge line. Fig 10 illustrates both the dry and wet sieving techniques.

Figure 10: Schematic view of Dry and Wet sieving process [42]

2.5.3 Sub-sieve Techniques

The sieving technique is used for the sample with size range bigger than 38 microns. Below this size sub-sieve techniques are used for particle size distribution.

2.5.3.1 Sedimentation Method

Particles that have a median size of 62.5 micron or below can be tested using hydrometer analysis. This method is widely used in the lab after being first invented in 1927 [43]. Hydrometer analysis utilizes a scaled stem along with a weight bulb, and calculation of the particle size is done based on the specific density of the provided suspension at some specific timings [44, 45]. Due to its availability and inexpensiveness, it is routinely used in labs for particle size distribution. It is considered as a standard tool for fine fraction analysis [46]. In this process Stoke's Law of setting velocity is used to determine the particle diameter [47, 48]. Usually this procedure is valid for the particle of 2 microns to 20 microns.

During hydrometer analysis, the particle sample is dispersed in distilled water and a dispersing agent like Sodium Hexametaphosphate is used with the solution to prevent flocculation of the particles. ASTM type 152H hydrometer used in the test and different correction factors are utilized for proper calculation of particle size distribution [45].

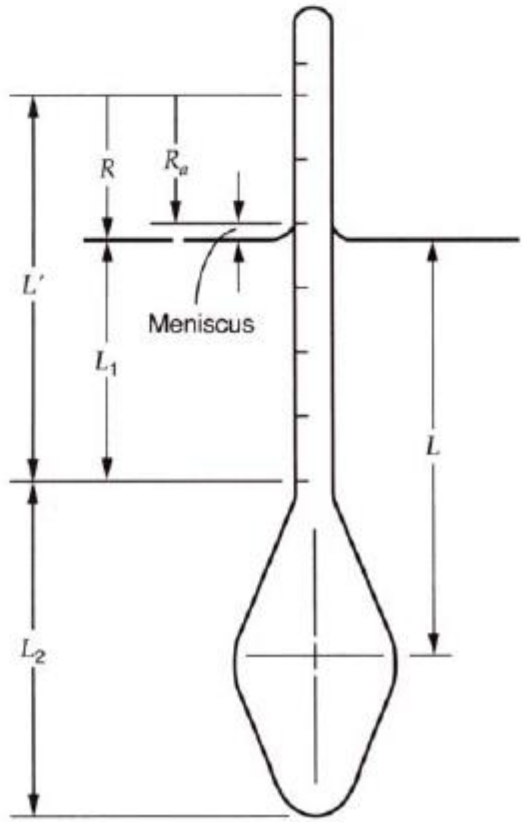


Figure 11: ASTM 152H Hydrometer [49].

2.5.3.2 Laser diffraction Method

Particles of a given size diffract light in the laser diffraction method through a given angle that is inversely proportional to the particle size [50]. This method can rapidly measure the dimension of a particle using diffraction patterns of a laser beam passing across any object [51].

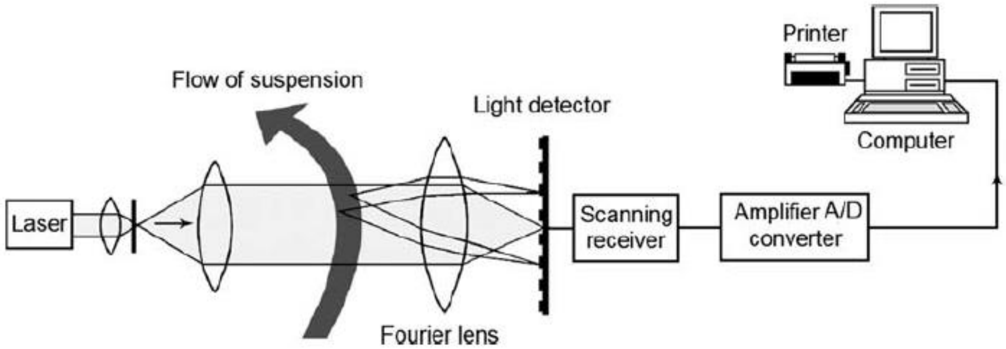


Figure 12: The laser diffraction method principle [52].

The laser diffraction device has a central measuring unit and a dispersion unit. Two semiconductors are placed in the central measuring unit that can measure the particle size ranges from 0.08 microns to 2000 microns [53]. This method uses several detectors to cover different size classes in the sample. When photodetectors generate the data, this data is transmitted to a computer and processed by this computer to generate a multichannel histogram representing particle size distribution [40].

2.5.3.3 Microscopy and Image Analysis

Considerable research efforts have been conducted in the development of methods that could provide detailed particles size distribution of size range of less than 2 microns. To measure and observe all individual particles of a sample, microscopic analysis is the most useful method [54]. The image analysis method can be performed in the lab on-line or off-line and also in the field while samples are moving on the shaker table as it accepts samples as photographs, electron micrographs, and direct observation [55].

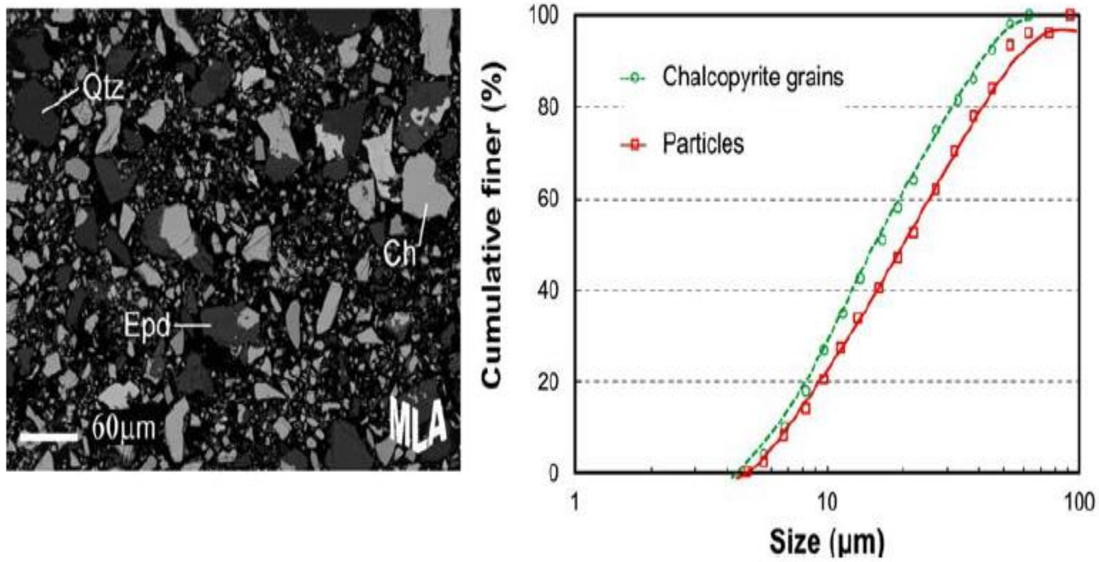


Figure 13: Generation of PSD using Image analysis method [55].

2.5.4 Presentation of particle size distribution of drill cuttings

Characterization of the particle size can be done by mentioning the size in respect to a specific variable - like the size of the mesh on which the particle was retained. In the sieve analysis method, the result obtained from the test is recorded as the particle weight that was retained on each sieve. The weight of the particle in each sieve is then converted to weight percentage of each class size by dividing each weight by the total weight of the sample and then multiplied by 100. This particle weight percentage can be converted to the particle weight percentage that passes through to the next biggest sieve size. After this conversion, the cumulative weight percentage is calculated by summing up the percentage of the particle weight starting from the finest size of a sieve [56].

Table 1: Example of a particle size analysis data used to generate PSD diagram

Sieve Size	**Gross Weight**	**Plate Weight**	**Weight Retained**		**Weight Passing**	**Cumulative weight**
(mm)	(gm)	(gm)	(gm)	(%)	(% finer)	(% finer)
<0.075	361.8	360.4	1.4	1.68		
0.075	319.2	310	9.2	11.09	1.688782	1.68
0.15	338.2	316.1	22.1	26.65	11.09771	12.78
0.25	339.9	335.8	4.1	4.94	26.65862	39.44
0.315	353.2	333.3	19.9	24.00	4.945718	44.39
0.63	375.5	367.7	7.8	9.40	24.00483	68.39
0.85	436.8	422.4	14.4	17.37	9.408926	77.80
2	464	460	4	4.82	17.37033	95.17
Total			82.9	100		

After generating the record data file, representation of these data points is the most vital part for proper understanding of the particle size distribution. The particle size distribution (PSD) diagram is plotted to represent particle size analysis data. The PSD diagram or graph is plotted by using sieve size in mm as the x-axis and the cumulative weight percentage as the y-axis. Logarithmic graph papers are used to generate the graph's y-axis or cumulative weight percentage and it is presented in logarithmic scale for better visualization.

When comparing different samples of drill cuttings, percentile values are needed to be read off the graph. A percentile is a representative of a size class that can be measured from the cumulative distribution curve for the finer value of a specific percent. From these types of graphs there are typically 7 type of percentile values that can be used such as D_{50}, D_{75}, D_{25}, D_{16}, D_{84}, D_5 and D_{95}. For example, if it is found that D75 is 65 mm that means that 75% of the particles are finer than this particular size. These percentiles values can be easily read from the cumulative weight percentage vs the sieve size graphs.

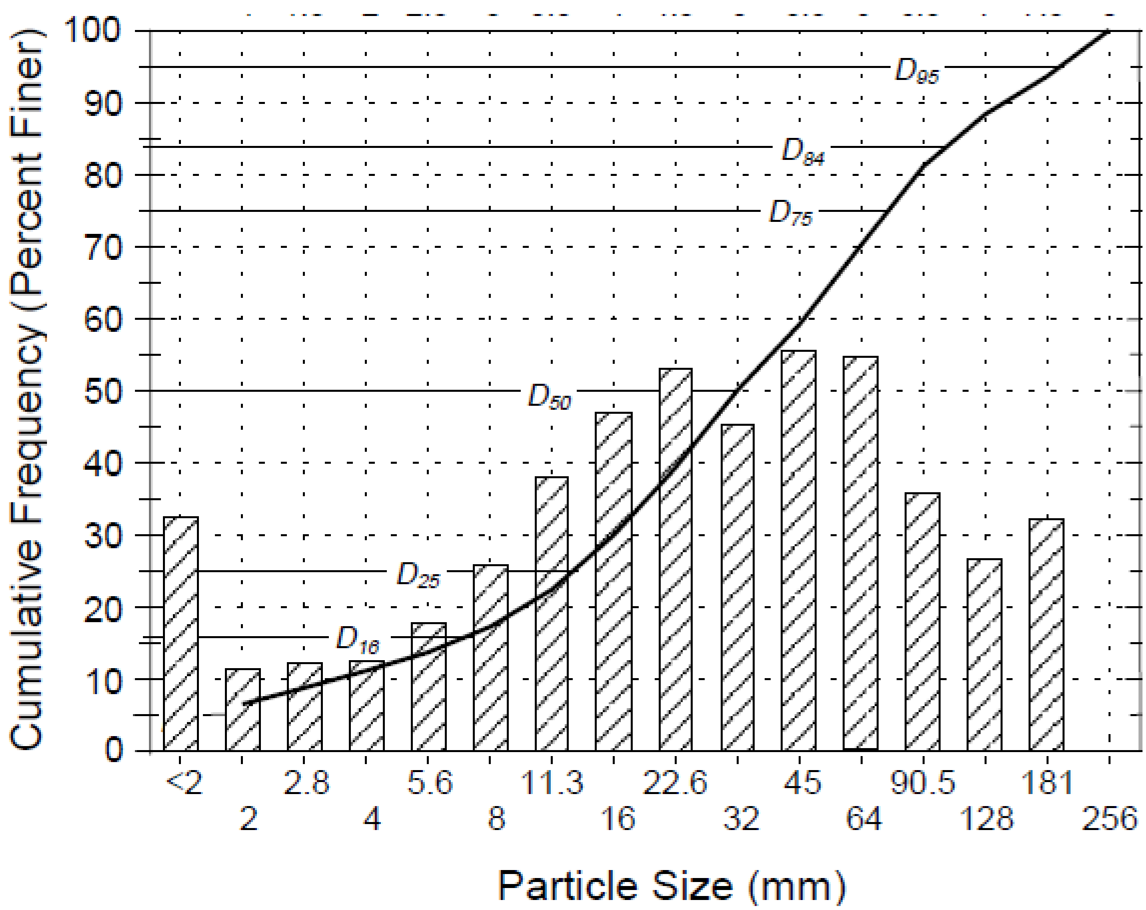


Figure 14: Illustration of cumulative weight percentage graph with indications of percentile values [56].

These percentile values can be mathematically calculated by using the logarithmic interpolation equation between two known data pairs. For instance, to find the value of D_{16} the following equation can be used [56].

$$D_{16} = 10 \wedge ((\log x_2 - \log x_1) \cdot (\frac{16 - y_1}{y_2 - y_1}) + \log x_1) \qquad (2.1)$$

This equation can be understood by using the data from the table 1. Here, x_1, x_2 values are the sieve size of 0.15 mm and 0.25 mm, and y_1 and y_2 are 12.78, 39.44 subsequently, the values of the cumulative weight percentage as D_{16} lies between 12.78 and 39.44 cumulative frequencies.

The Bar Particle Size Distribution or the BarPSD graph can also be used to present particle size distribution data. This is a visual representation of the PSD diagram in a series of bar diagrams where the weight percentage of each sample presented as a function of depth [57].

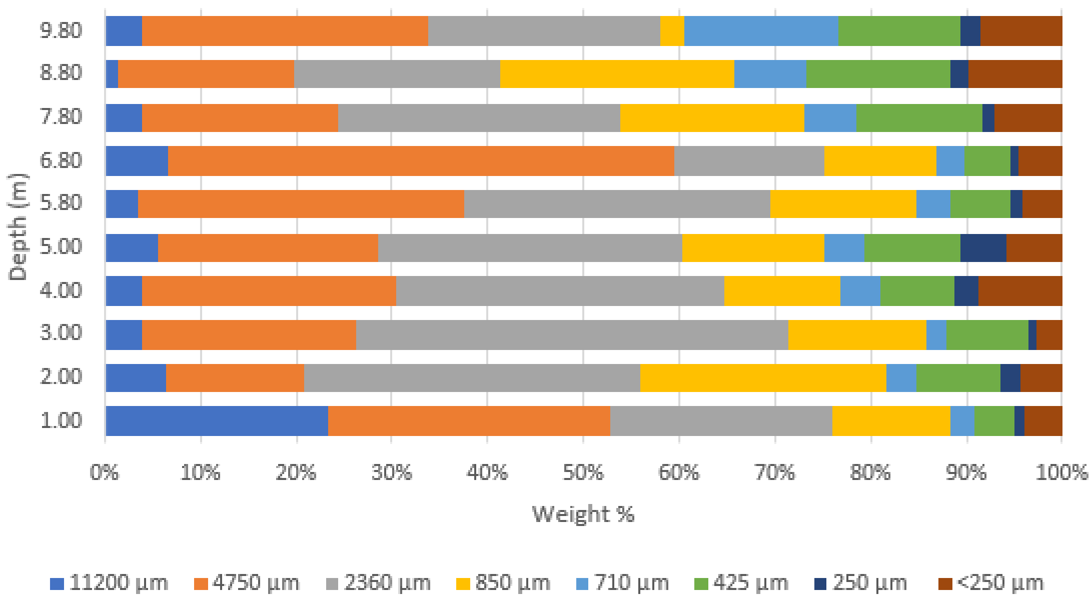


Figure 15 Example of a BarPSD diagram

Particle size distribution can also be characterized by the median and mean particle size. Median particle size is the center value of the cumulative weight percentage that divides the group of sizes into two parts. D_{50} is the median particle size which expresses that 50% of the particles are finer that that particular size.

Mean particle size is broadly used in describing PSD quantitatively. The Rosin and Rammler model (1933) is the first proposed model to calculate the mean particle size diameter. $D_{36.79}$ is also called the mean particle size [58]. By using the MATLAB coding proposed by Brezani and Zeleank in 2010, mean particle size can be calculated. The equation used for the R-R model is as follows [59]:

$$R(d) = 100 \exp [- (\frac{d}{d_m})] \wedge n \qquad (2.2)$$

Where,

R(d) = cumulative weight percentage

d = particle size (microns)

dm = mean particle size (microns)

n = measure of the spread of the particle sizes distribution parameter.

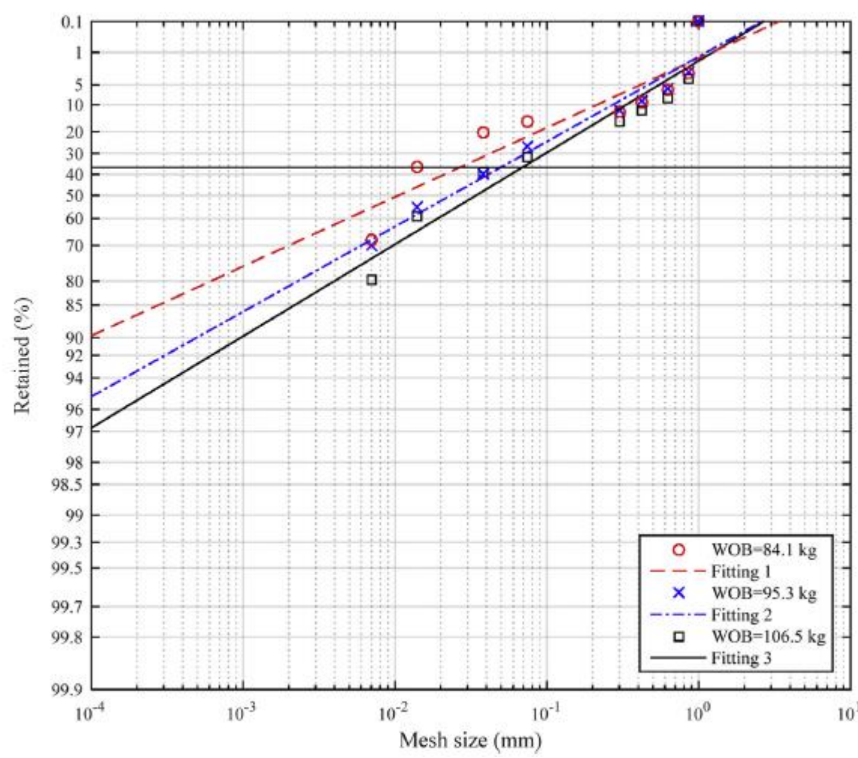


Figure 16: Illustration showing the graph for calculating Mean Particle Size [60].

Particle size distribution can also be presented by the Coarseness Index (CI). In 1973, Roxborough and Rispin described CI as a non-dimensional number that can be obtained by summing up all the cumulative weight percentages of all particles retained in each sieve. This index can characterize the overall sample by using a number. Comparing between samples is easier with this method. The equation for calculating the CI is written below where W_i is the weight percentage of different fractions [61].

$$\mathrm{CI} = \sum_{n=1}^{i} (W_i + W_{i+1}) \qquad (2.3)$$

2.6 Drilling performance evaluation applying cuttings particle size analysis

Particle size distribution from different operations in different industries contains vital data about each process. For the last few decades researchers have been studying the relation between drilling performance and penetration mechanism from particle size distribution of the drill cuttings [57, 60, 62,63].

Drilling performance can be evaluated by assessing the penetration rate and energy consumed during creation of new surface areas. Rittinger, first mentioned this form of evaluation in 1867 and stated that introducing new surfaces consumed most of the penetration energy and that energy is inversely proportional to the size of the particles [64]. Geometrical changes of the size of the particle require more equivalent energies [65]. The specific energy (SE), which is an indicator of the efficiency of the excavation and is defined as the energy needed to excavate a unit volume of rock, assumes that for a given rock and type of tool, a decreasing trend with an increasing particle size obtained from the rock fragmentation process. Teale (1964) concluded that the specific energy required to drill a rock increased considerably as rock particles started to break needlessly and caused decreased particle size [66]. From cutting test experiments performed on different types of rocks with a CCS type disk cutter and conical disk cutter a strong relationship between specific energy and the Coarseness Index (CI) was found.

$$SE = k.(1/CI^n) \qquad (2.4)$$

The parameter k is a function of rock strength and cutting tool parameter. n is around 2.2-4.4 for conical cutters and 5.5 for CCS disk cutters [67]. Data generated from field investigation of excavation of a tunnel of 6.3 m diameter showed that there is an inverse relationship between specific energy (SE) in MJ/m^3 and the Coarseness Index (CI). The relationship is as follows [68]:

$$SE = -0.2737*CI + 102.91; (R^2 = 0.734) \qquad (2.5)$$

From the field data analysis of a TBM, relationship between CI and depth of cut (d) in mm/rev was obtained as [67]:

$$CI = 91.40*d + 418.18 \qquad (2.6)$$

Researchers also investigated the data and particle size of a Tunnel Boring Machine (TBM) of 2m diameter and observed that larger chips of the average size of 14–15 cm long, 6–7 cm width and 0.6–0.8 cm thickness were obtained in optimum conditions. It was concluded in their paper that for all the samples D50 ranges from 12.9 mm to 49.9 mm meaning that 50% of the particles are finer from this size range. The max diameter of the particle was found to range from 80 mm to 196.5 mm. Several studies show that both the rate of penetration and the particle size distribution of the debris are strongly influenced by the rock mass characteristics and especially by its fracturing [68].

Size distribution of the muck obtained in the mechanized excavation operations are used for determining the efficiency of cutting. The muck size is a good indicator of the main characteristics of the geological formation and the efficiency of drilling operations. In a boring operation with a Raise Boring Machine (RBM) with 3.1 m ream diameter, the CI values were estimated for the pilot and reaming operations to be 559 and 764, respectively, indicating that reaming operations are more efficient than pilot drilling due to the difference in operations and equipment. From size distribution graph it was found that for pilot hole D50 was approx. 2.5 mm and for reaming it was approx. 6.5 mm. The muck obtained from the reaming operations was coarser than the muck obtained from the pilot drilling operation emphasizing the efficiency of reaming operations since specific energy decreases with the coarseness index [69].

Some investigators assessed the types of particles created from linear cutting tests on dry and saturated sandstone. They performed full scale disk-cutting tests on rock samples with the UCS of 51 MPa and found that D50 was bigger than 55 mm and that the absolute size constant was 90 mm meaning that that is the most common size in particle distribution. From data analysis an overall decreasing trend of SE with an increasing CI was observed [70].

Extensive research was performed by excavating a tunnel to learn about boring methodology and the particle size distribution and the shape of the crushed rock resulting from the boring process. Three 1.5 m diameter tunnels were bored in anisotropic tonalite formation of 80 MPa UCS. On the cutter head two types of cutter assemblies were installed for investigation. From their observation they found that the particle size of 56- 64 weight-

% of the crushed rock was less than 1 mm. The average particle size, D_{50}, of the crushed rock was 0.4 - 0.6 mm. The difference in particle size that resulted from the use of different thrust levels was small. In general, particle size decreased as rotation speed was lowered. The difference was apparent with both types of cutters. The large quantity of fine particles indicated the regrinding of crushed rock. The average thickness of the particles was 5.5 mm, the average length was 16.9 mm and the average width was 13.2 mm. The thickness of the largest particles seemed to be slightly reduced when the thrust was increased [71].

In a study by L. Gertsch in the USA in 2000, several case histories were evaluated to characterize the particle size of the chips generated and he summarized the studies of bored tunnel projects. They found the largest chips produced are of 300 mm length and 150 mm width [72]. Other observations are listed in the following table:

Table 2: Drilling and particle size parameters from the tunnel project of year 2000 [72].

Formation	**UCS**	**Diameter (m)**	**RPM**	**Thrust (MN)**	**D50 (mm)**	**D90 (mm)**
Sandstone	152	5.5	4.5	4007	19.5	24
Limestone	179	3.2	6	1000	18.6	24.5
Sandstone	69	3.9	5.2	1590	13.9	28
Quartz	221	3.7	6	2260	14.77	23
Quartz	48	1.2	6	290	12.3	23
Limestone	165	3.4	9.3	2840	19.41	24.3
Quartz	76	3.4	10.75	5040	10.81	21.6
Sandstone	21	6.25	8	2730	19.57	28.5

Drilling experiments were performed by using a PDC bit and an impregnated diamond core bit with fixed drilling conditions to observe connections between drilling parameters and drilling detritus [63]. Researchers found relationship between particle size and different drilling input and output parameters and wrote the lines of conclusion stating that both the ROP and WOB increased with bigger particle size with the same type of trend (fig 17). Rotary speed was also found to increase with reduced particle size.

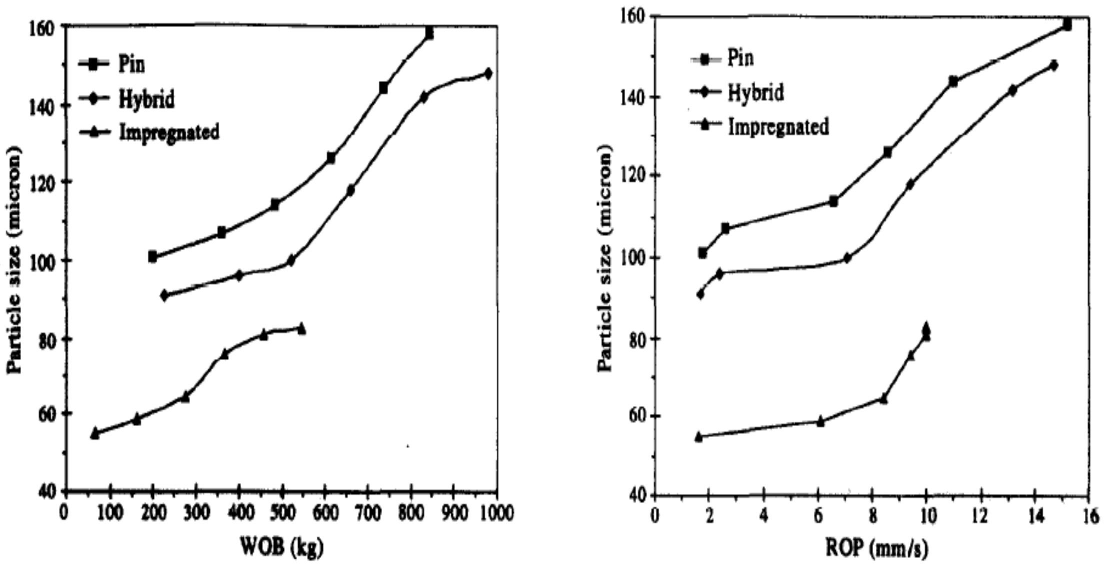


Figure 17: Graphs showing how particle size increases in response to increasing WOB and ROP [63].

Pfleider and Blake (1953) found a rough relationship between the rate of penetration and the particle size of drill cuttings as higher ROP produces bigger particles during drilling [73]. Drilling experiments using impregnated diamond bits showed that drilling parameters like ROP, RPM, axial load and other parameters have huge influence in drilling detritus size [74].

The study of finding the relationship between energy consumption when drilling and particle sizes revealed that mechanical specific energy increased as the minimum particle size decreased [75]. A general decreasing trend of MSE is observable as the minimum particle size increases. The generated equation is as follows:

$$MSE = 103736*e^{(0.901*D_{min})} \qquad (2.7)$$

For the mean particle size distribution, a relation between the MSE and D^{-1} was obtained as shown below.

$$MSE = 19{,}875D_{mean}^{-1} + 44683 \qquad (2.8)$$

Where, MSE is in psi and particle size is in micrometer.

Finer particles generate when regrinding or crushing of the particle occurs beneath the drill bit due to poor transportation of the cuttings to the surface which leads to more energy consumption and increment in MSE. The depth of cut (DOC) also has influence on the particle size as a higher DOC generates coarser cuttings in general [76].

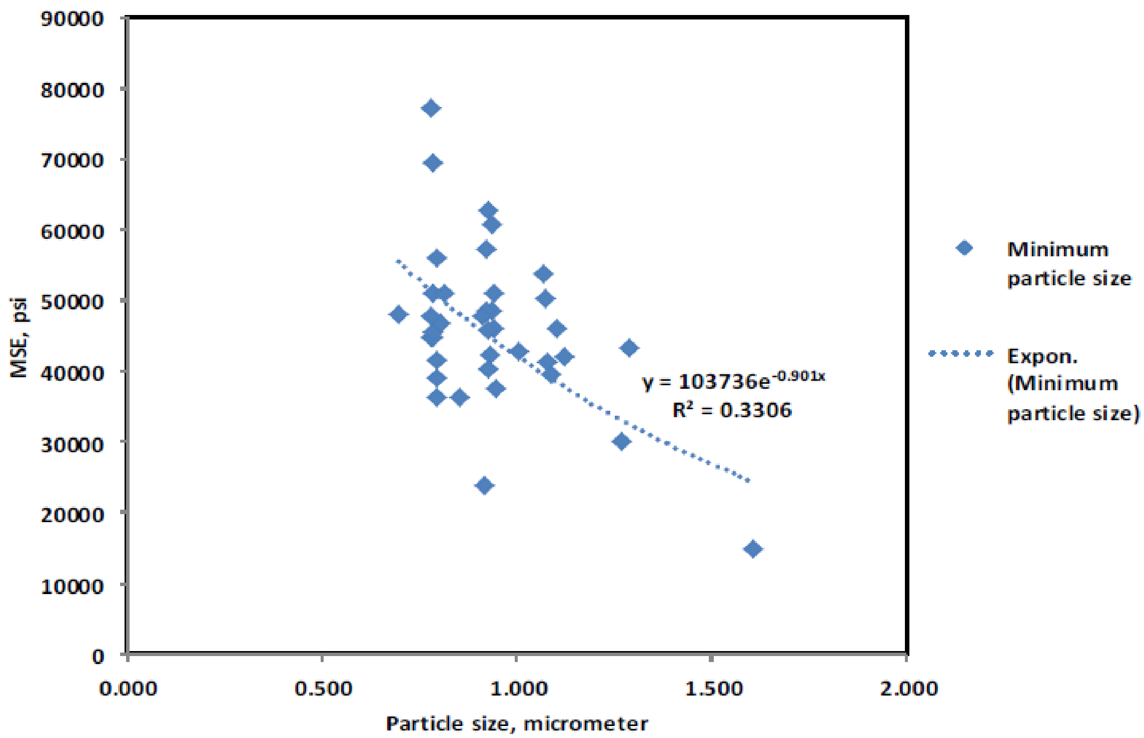


Figure 18: Illustration of MSE vs particle size as MSE decreased with bigger particle size [75]

An investigation was conducted by researchers to study different particle size distribution parameters in relation with drilling performance. It was found from the study that the coarseness Index (CI) increases with an increased penetration rate and a similar trend was also observed in active vibration drilling between mean particle size, weight on bit and penetration rate as high mean particle size indicated better drilling performance [60]. The study also observed a reduction in the rate of penetration as the specific surface area of the drilled rock increased [76]. Figures 19 and 20 below illustrated these relationships.

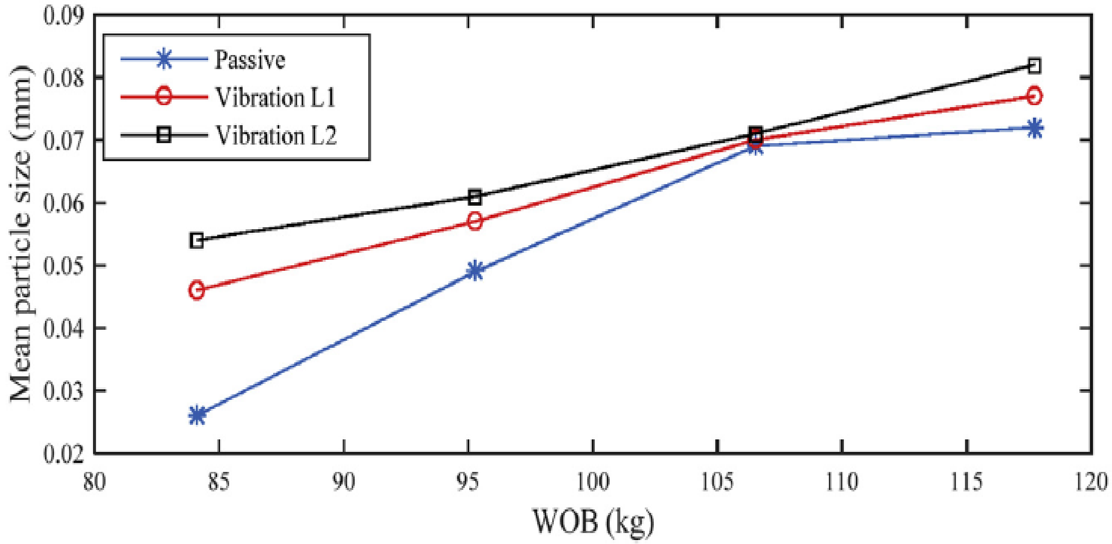


Figure 19: Positive relationship found between mean particle size and WOB [60]

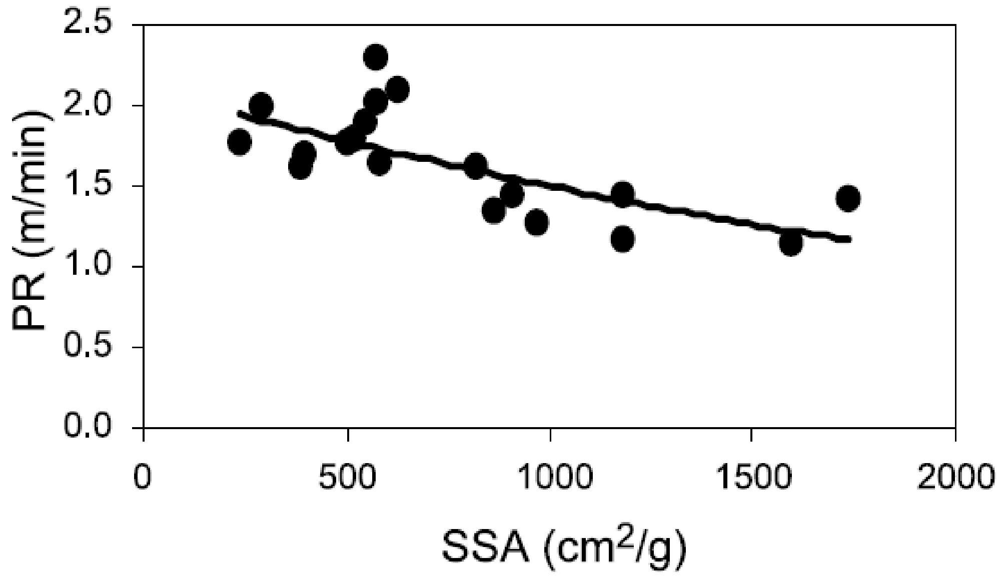


Figure 20: Showing penetration rate decreasing as specific surface area increasing [62]

In 2003 and 2004, Altindag developed some equations to predict the penetration rate for percussive drilling by using the CI and the mean particle size. The penetration rates were correlated with the coarseness index and the mean particle size by using the method of the least square regression. The relationship developed is as follows:

$$PR = 0.257*e^{(0.0032*CI)} \qquad (2.9)$$

$$PR = 0.9185*e^{(0.2795*CI)} \qquad (2.10)$$

Where, the PR is in m/min and the mean particle size is in mm. Another relationship between penetration rate and coarseness index with mean particle size was investigated through the multi-regression analysis. The equation is:

$$PR = 0.00325(CI) + 0.193(d) – 0.583 \qquad (2.11)$$

Altindag concluded in his study that there is an exponential relationship between the penetration rate and the coarseness index. A high coarseness index shows a high penetration rate. A meaningful exponential correlation exists between the penetration rate and the mean particle size. High mean particle size value shows a higher penetration rate in the percussive drilling process [62, 76].

A study done by Suraj et al in 2017 investigated the drill cutting parameters and their significance in drilling performance (fig 22). From the drill cuttings analysis, they found a relation between the PR and the mean diameter as follows [77]:

$$PR = 0.216*\ln(d) + 0.5696 \qquad (2.12)$$

$$PR = 0.6103*e^{(0.0784.d)} \qquad (2.13)$$

The relationship between PR and the CI is found to be exponential. The equation is:

$$PR = 0.1874*e^{(0.0028*CI)} \qquad (2.14)$$

Where, PR is in m/min, mean diameter is in mm.

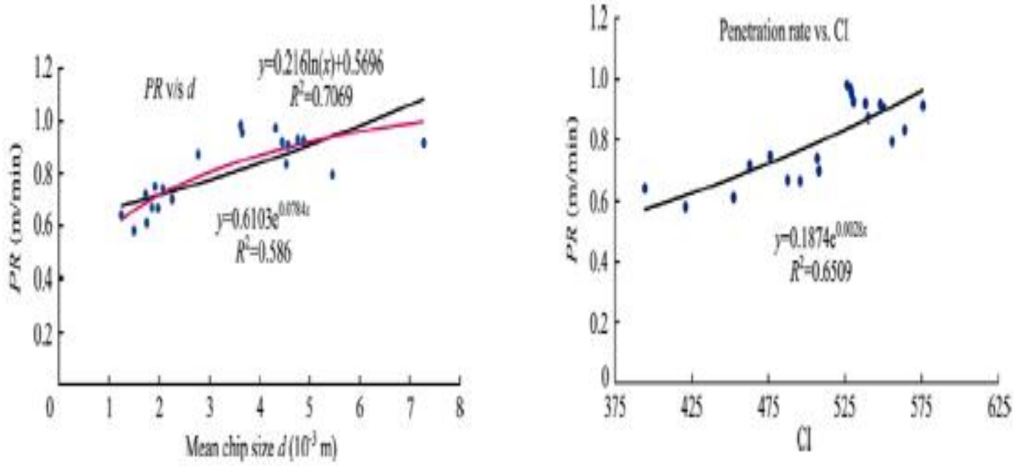


Figure 21: Graph showing relationship between Penetration Rate, CI and mean diameter [77].

While studying the drilling efficiency and the performance evaluation of a passive Vibration Assisted Rotary Drilling (pVARD) tool, researchers found that the mean particle size, the CI has a positive relationship with the ROP and the WOB, and that both the mean particle and the CI increased with increasing drilling parameters [57]. In the course of the hole widening drilling operation study the relationship between the drilling parameters and the particle size was evaluated and was stated that in the hole widening drilling ROP increases with the increase in the WOB and produces coarser particles following the trend [78]. All the above mentioned studies worked on finding relationship between particle size of the drill cuttings with the drilling parameters for only single pass drilling method.

However, these studies do not talk about the relationships for hole widening drilling process. In this study relationship has been evaluated for hole widening drilling process and how hole widening drilling process show better performance in comparison to pilot hole drilling was established.

Chapter 3: Evaluation of Hole Widening Drilling Process Combining Drilling Response, Drilling Performance, and Cutting Analysis.

This chapter contains the paper titled “Investigation of Hole Widening Drilling Using Cutting Analysis”. This paper is authored by Daiyan Ahmed, Yingjian Xiao, Jeronimo De Moura Junior and Stephen D. Butt and was published through the proceedings of Geo St.John's 2019, the 72nd Canadian Geotechnical Conference, St John’s, Newfoundland, Canada. To be noted that some figures were modified for better presentation in the thesis.

3.1 Abstract

In Narrow Vein Mining (NVM), mining excavation commonly switches from open pit mining to drilling excavation based on projected cost and efficiency. Mining drilling is generally conducted on a 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. The drilling performance of pilot hole drilling and hole widening drilling was evaluated based on the following parameters: rate of penetration (ROP), torque, and 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 with 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 executing the drilling plan for a hole widening operation for narrow vein mining.

3.2 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 the surface [79]. These three parameters are generally called bit operating conditions. During the 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 drill string exterior.

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

The drilling performance of a well is measured by the time taken to construct the wellbore. The main goal for the operators is typically to achieve a 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

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 governed by three groups of parameters: rock characteristics, machine parameters and operating processes [62]. Different researchers worked earlier to establish a relationship between these three parameters and cutting analysis; one study concluded that the particle size of the cuttings becomes coarser as the ROP increases [73].

Drill cuttings work as a 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. [57]. According to Pfleider et al. (1953), the size of the cuttings is strongly related to ROP and this ROP depends on 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 cannot be achieved perfectly [73].

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

3.3 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.

3.4 Materials

A granite block was used to perform the drill off test. The dimension of the granite block was 12 inch in length, 12 inch in width and 8 inch in height (fig 22). 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 22: Granite Block used in DOT

3.5 Drilling System

A small drilling simulator was used to drill the pilot hole and enlarged hole (fig 23). Tap water of a constant flow rate was used to perform the drilling and cleaning of the hole. WOB was applied using a mass suspended on a wheel. The rotation was provided by a rotating motor which can produce two different settings of rotary speed, 300 rpm and 600 rpm. 300 rpm was used in this lab experiment.

Figure 23: Small Drilling Simulator (left) and cutting collection system installed (right)

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

3.6 Overview of Cutting Size Analysis Procedure

After each run of the 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 and cutting collection procedure from researchers of DTL was followed for proper collection of cuttings [41, 57]. After collection, cuttings were put in the oven for 12-14 hours and dried at the temperature of 60-70 degree Celsius. The entire sample was subsequently sieved for analysis.

Different sizes of cuttings were sieved with mesh sizes of (fig 24): 2 mm, 850 micron, 630 micron, 315 micron, 250 micron, 150 micron and 75 micron.

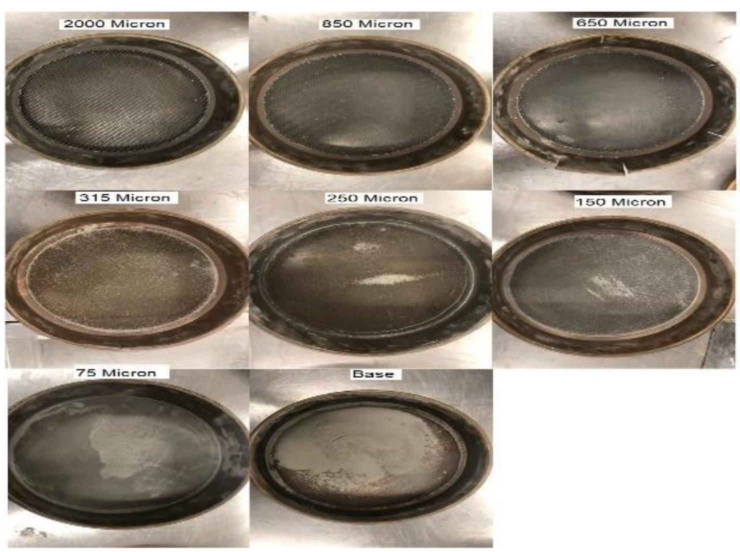


Figure 24: Different sieve sizes used for sieve analysis

An automatic sieve shaker was used to separate different sizes and then the weight of each sieve mass was measured for particle size analysis (fig 25).

Figure 25: Oven and standard sieving machine used to sieve analysis

3.7 Results and Analysis

During each drilling, cuttings were collected, and the cumulative weight percentage of passing particles was calculated from the 12 cuttings samples generated by the lab experiment. Particle size distribution diagram (PSD) is a 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. This data can be used for further analysis of drilling performance.

3.7.1 Drilling Performance Evaluation

By using a small drilling simulator, DOTs were conducted, and different drilling parameters were analyzed for the evaluation of drilling performance. Drill-Off Tests were conducted on the granite block with a rotary speed of 300 rpm. For different bits and different WOB, depth vs time graphs and vibration vs time graphs were created (fig 26). These graphs were then used to generate ROP and RPM for different configurations.

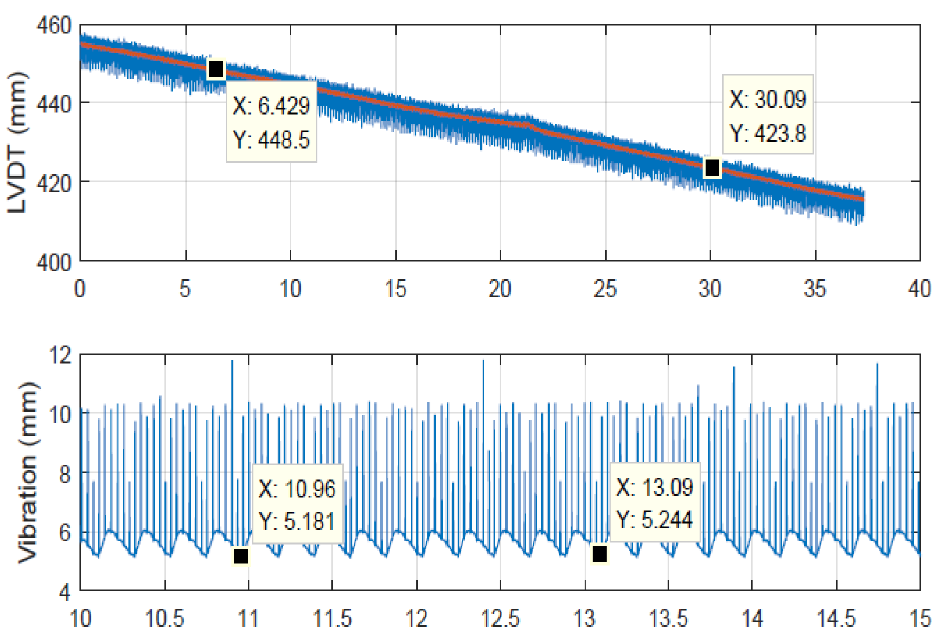


Figure 26: Depth vs Time and Vibration vs Time graphs from where ROP and RPM was calculated

Four different types of WOB were applied to drill bits using suspended mass from the wheel. These WOBs depend on number of steel plates suspended from the wheel which make different value of weights. Table 3, below, shows the relation between numbers of plates with WOB in Kg.

Table 3: 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. The second one is for coring bit, and the third one is for enlarging the 26.4 mm drill hole to 32.4 mm hole using a PDC bit (fig 27).

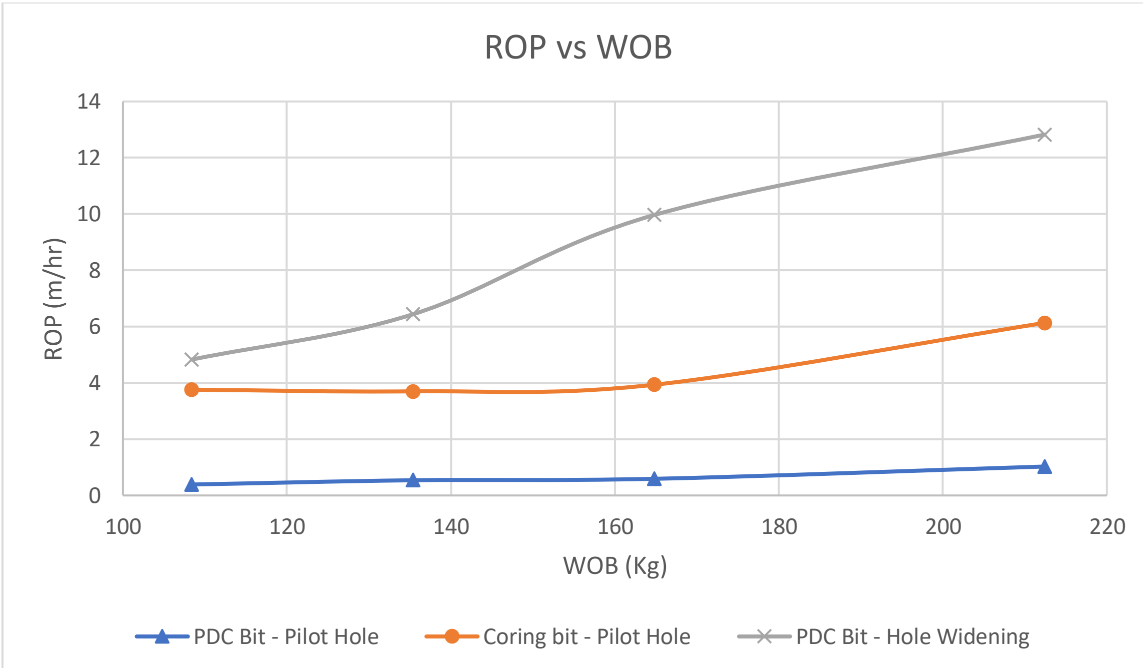


Figure 27: ROP vs WOB obtained from lab experiments for three different conditions

From this figure it is shown that ROP increases as a function of increasing WOB for each drilling condition. During the lab experiment, the RPM that was obtained was not the same as the one that generated by 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 calculated from the main ROP multiplied by the ratio of nominal rotary speed over the actual speed and the normalized rotary speed was obtained from the ratio of actual rotary speed over the nominal one [80]. Figure 28 and 29 below show the relation between normalized ROP and normalized resulted RPM with WOB. Here, RPM decreases with increasing WOB and for the hole widening operation it is the lowest. This occurs because the pre-existing hole makes drilling with PDC bit more challenging and more energetically expensive. Normalized ROP is greater than actual ROP for all drilling conditions because of deduction of rotary speed in normalized condition.

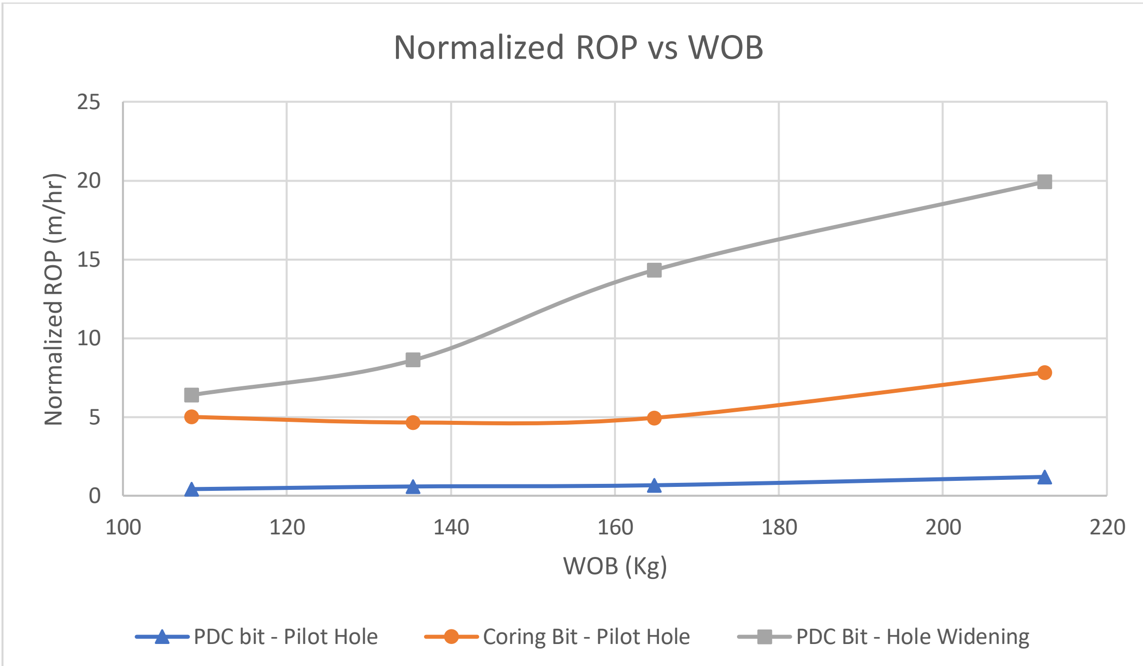


Figure 28: Graphs showing normalized ROP as a function of WOB.

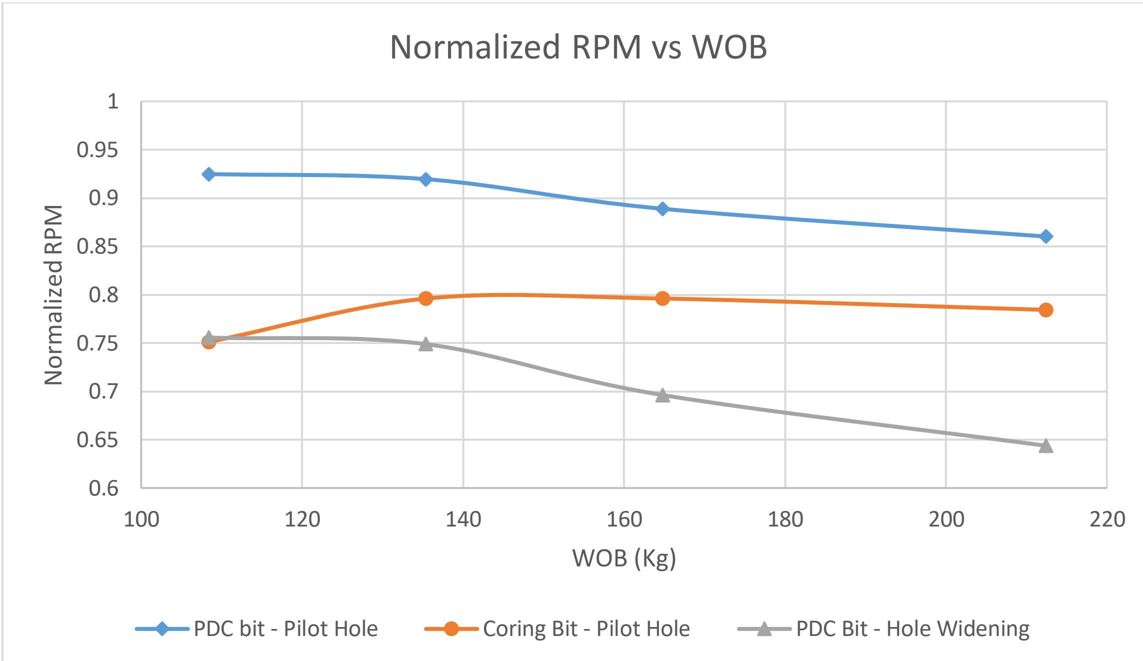


Figure 29: Graphs showing normalized RPM as a function of WOB.

Figure 28 and 29 show that the ROP for the PDC bit in pilot hole drilling is unsatisfactory, whereas for hole widening drilling with same PDC bit it increased drastically. This increase may occur because PDC is not a good bit to use in hard formations. The granite block that was used in the experiment was a hard rock. PDC bit does not show a remarkable penetration rate in hard rock compared to soft formations.

On the other hand, the same PDC bit showed a noteworthy penetration rate in the hole widening operation. This can be analyzed by Maurer's Perfect Cleaning Model. According to the work of W. Maurer, first published in 1962, ROP varies directly with the RPM and the square of WOB. And it varies inversely with the square of the bit diameter and the square of the strength of the rock being drilled [81]. The equation is as follows.

$$ROP = \frac{K}{S^2} * \left(\frac{W - W_o}{D}\right)^2 * N \qquad (3.1)$$

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

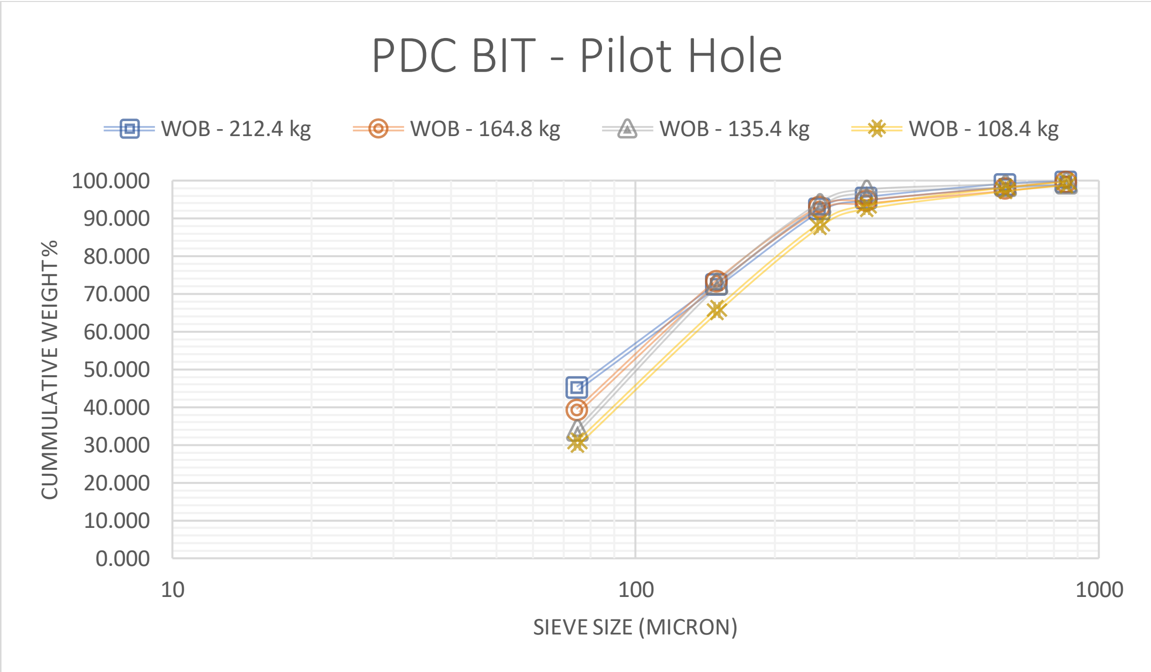
From the Maurer Model it is evident that ROP has an inverse relationship with the diameter of the hole which basically also represents the corresponding area of the hole. Hole widening is the process of enlarging a previously drilled hole into a new bigger hole with a larger diameter. As for the previously drilled hole, during the hole widening operation, the area below the bit is so small compared to conventional drilling, but it still 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 the hole widening operation using the PDC bit increased dramatically compared to pilot hole drilling.

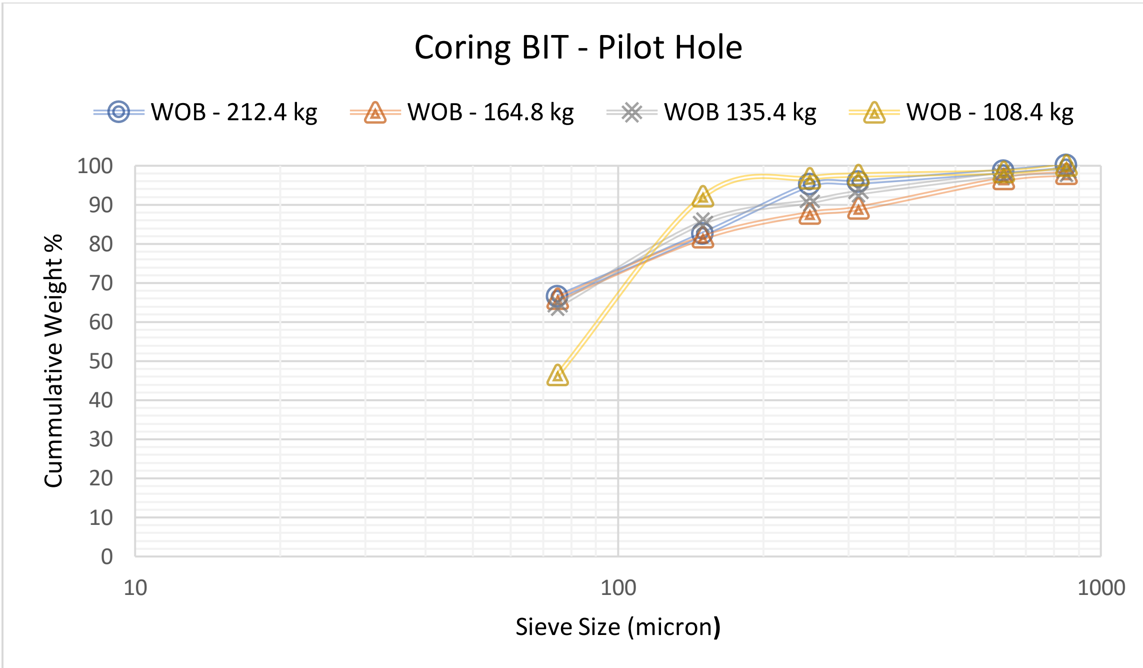
3.7.2 Particle Size Analysis

Particle Size Distribution diagram (PSD) is a convenient method to display the cutting size distribution. In the diagram, the Y axis is designated as the cumulative weight percentage and the 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 cuttings will be left in sieve.

The Particle Size Distribution diagram (PSD) was obtained for three different drilling conditions. As mentioned above, one is for the pilot hole drilling with PDC bit, one is for pilot hole drilling with Coring bit, and the last one is for the hole widening operation using the PDC bit. Size of the cuttings ranges from 10 micron to 2 mm. Figure 30 shows the PSD diagrams for different drilling conditions.





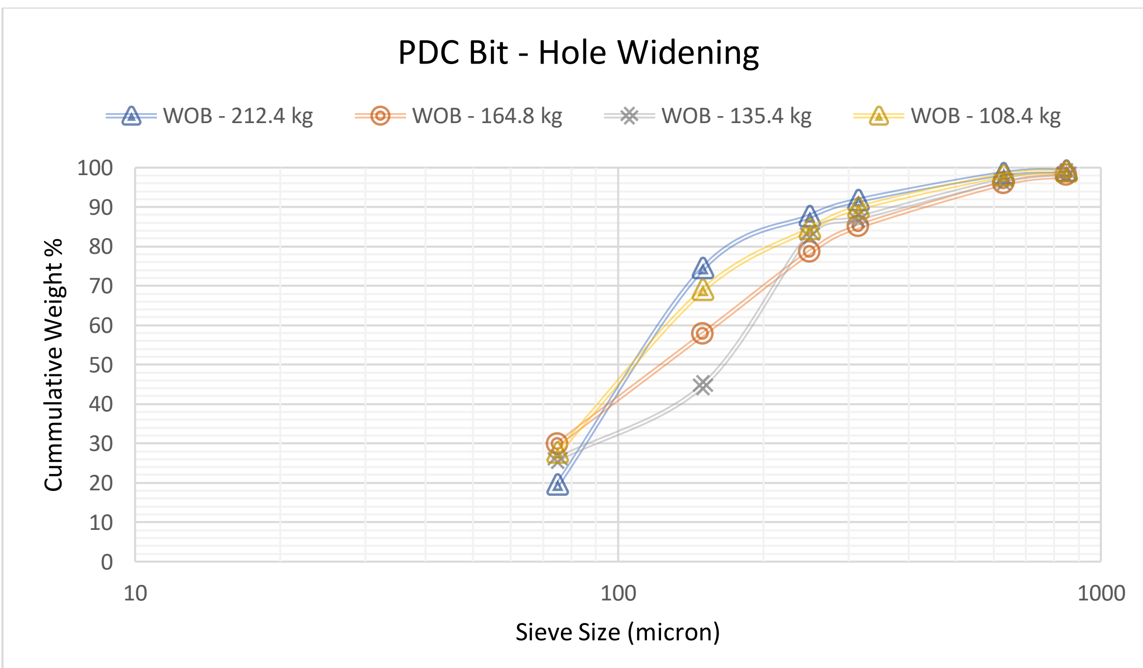


Figure 30: Particle Size Distribution (PSD) diagram for three different drilling operations

As seen in figure 30, it is obvious that the hole widening operations with the PDC bit cutting size is bigger and results in a higher WOB. For 212.4 kg WOB cutting size is coarser up to 100-micron range but for 164.8 kg WOB cutting size becomes larger than others as it moves to the right size. This may result from the higher WOB of 212.4 kg causing the particles begin grinding more while the164.8 kg WOB worked as the optimum weight for perfect crushing and hole cleaning. In general, cutting size is coarser for higher WOB.

Coring bits did not show proper results for cutting size distribution but for the PDC bit used in pilot hole drilling it followed a reverse trend. Here, less WOB produced coarser particles, potentially, because of hard rock. As PDC bit is not convenient for drilling in hard rock formations like granite.

Coarseness Index (CI) is another parameter to describe the size of the hole sample. It is a non-dimensional number that can be obtained by the summation of cumulative weight percentages of a particular size [61]. CI can be used to represent the size of the samples if the same sieves are used for all the sampling. By using the CI, overall samples can be characterized by one number, but it does not provide enough information about the sample size.

CI was calculated for 12 samples that were generated in the lab experiment with varying WOBs. The results of these calculations are shown in Table 4 below. From this table it is shown that a coring bit produces coarser particles than other two bits and hole widening operations using PDC bit produced overall finer size of particles.

Table 4 Coarseness Index for 12 different samples

WOB (Kg)	108.4	135.4	164.8	212.4
CI for PDC Bit – Pilot Hole	574	595	596	602
CI for Coring Bit – Pilot Hole	631	630	619	638
CI for PDC Bit - Hole Widening	567	536	545	571

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 31 shows the relation between ROP and CI for PDC bit in pilot hole drilling.

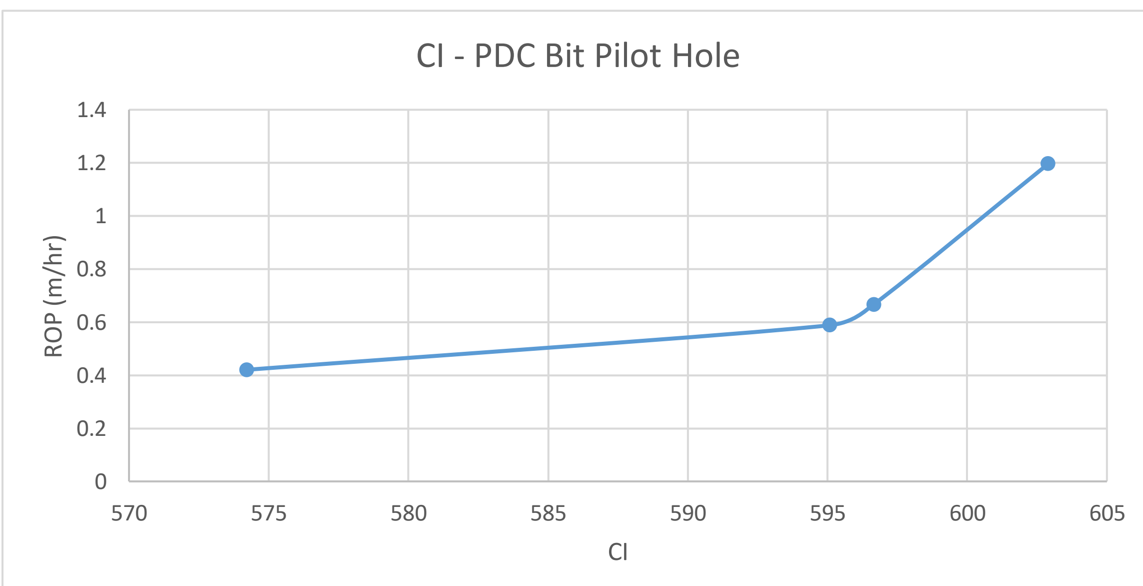
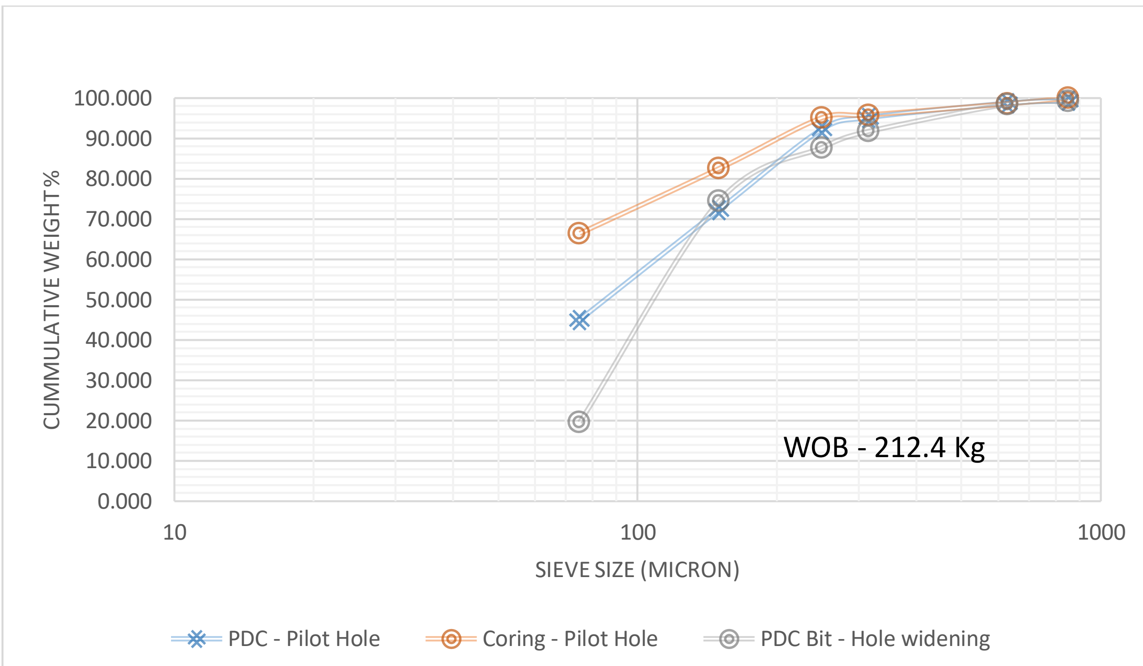
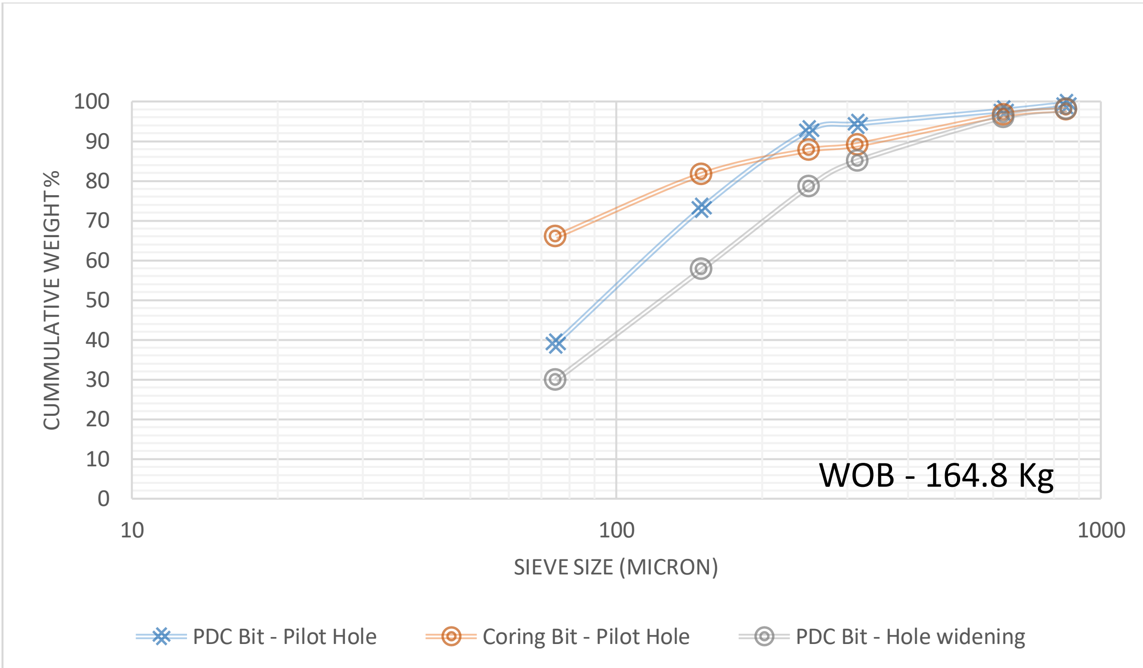


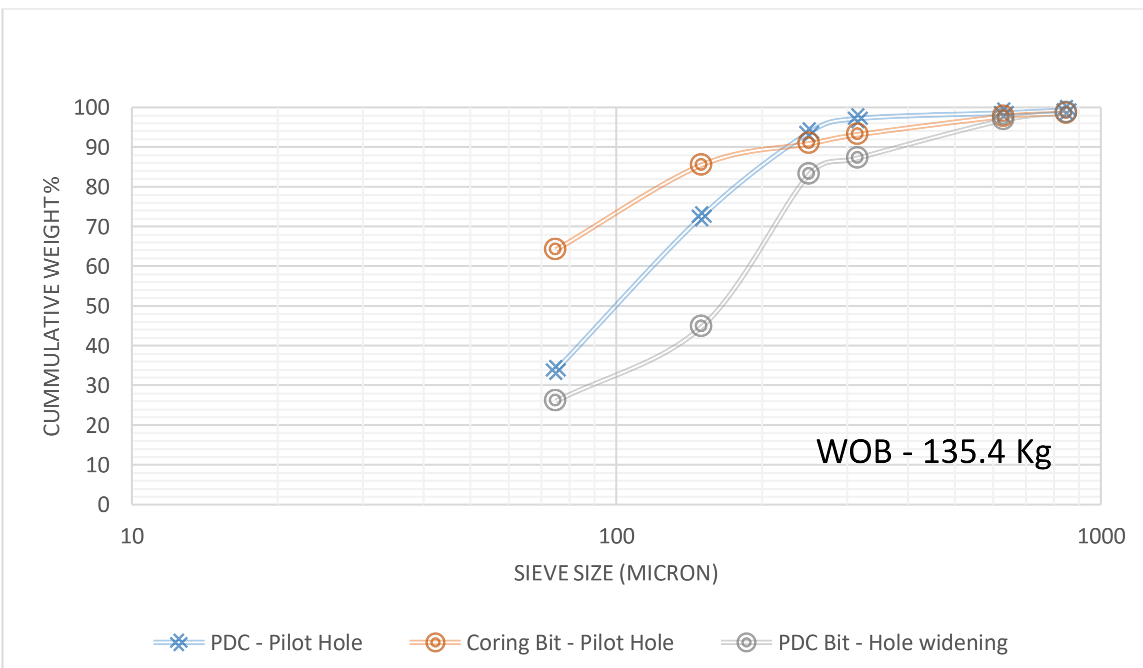
Figure 31: CI increases as ROP increases for PDC bit for pilot hole drilling

3.7.3 Particle Size Distribution for Different Bits

Particle size distribution was also investigated when WOB was held constant and the bit type was varied. It was found that for all hole widening operations the particle size was bigger relative to the other pilot hole drilling. Figure 32 shows the graphs representing the particle size relationship with different drilling settings.




100
90
80
70
60
50
40
30
20
10
0
CUMMULATIVE WEIGHT%
10
100
1000
SIEVE SIZE (MICRON)
WOB - 164.8 Kg
PDC Bit - Pilot Hole
Coring Bit - Pilot Hole
PDC Bit - Hole widening


100
90
80
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20
10
0
CUMMULATIVE WEIGHT%
10
100
1000
SIEVE SIZE (MICRON)
WOB - 135.4 Kg
PDC - Pilot Hole
Coring Bit - Pilot Hole
PDC Bit - Hole widening

Figure 32: Particle size distribution for different WOB and drilling settings

From the above figure it is evident that, higher WOB hole widening drilling generates bigger particles and coring bit produces the finer ones. For the lesser WOB of 108.4 Kg, PDC bits for pilot hole and hole widening drillings generate similar size cuttings. This trend indicates that a higher WOB tends to generate bigger particle sizes for hole widening drilling than it does for other conventional drilling.

3.8 Conclusions

From the results obtained from lab experiments and analysis, following conclusions can be made:

- 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 (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.
- 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.

Chapter 4: Drilling Cutting Analysis to Assist Drilling Performance Evaluation in Hard Rock Hole Widening Operation

This chapter discusses about the paper titled as "Drilling cutting analysis to assist drilling performance evaluation in hard rock hole widening operation" that was prepared for publication in the proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering OMAE2020, FL, USA. This paper is authored by Daiyan Ahmed, Yingjian Xiao, Jeronimo de Moura, and Stephen D. Butt. The M.Eng candidate was involved in preparing experimental plan, experiment plan execution, data analysis and writing the paper for publication. Note that some sentences were modified and corrected.

4.1 Abstract

Optimum production from vein-type deposits requires the Narrow Vein Mining (NVM) process where excavation is accomplished by drilling larger diameter holes. To drill into the veins to successfully extract the ore deposits, a conventional rotary drilling rig is mounted on the ground. These operations are generally conducted by drilling a pilot hole in a narrow vein followed by a hole widening operation. Initially, a pilot hole is drilled for exploration purposes, to guide the larger diameter hole and to control the trajectory, and the next step in the excavation is progressed by hole widening operation. Drilling cutting properties, such as particle size distribution, volume, and shape may expose a significant drilling problem or may provide justification for performance enhancement decisions. In this study, a laboratory hole widening drilling process performance was evaluated by drilling cutting analysis. Drill-off Tests (DOT) were conducted in the Drilling Technology

Laboratory (DTL) by dint of a Small Drilling Simulator (SDS) to generate the drilling parameters and to collect the cuttings. Different drilling operations were assessed based on Rate of Penetration (ROP), Weight on Bit (WOB), Rotation per Minute (RPM), Mechanical Specific Energy (MSE) and Drilling Efficiency (DE). A conducive schedule for achieving the objectives was developed, in addition to cuttings for further interpretation. A comprehensive study for the hole widening operation was conducted by involving intensive drilling cutting analysis, drilling parameters, and drilling performance leading to recommendations for full-scale drilling operations.

4.2 Introduction

Many ore deposits explored in Canada are not feasible for extraction by conventional mining methods. These deposits are found trapped in narrow veins. Mining by drilling is a process by which narrow vein mines can be excavated economically. In the USA, large-diameter hole drilling was introduced first in the late 1950s and large diameter holes hit the footage of 5000 ft to 11700 ft after 1953 with the use of large diameter hole openers [82]. Earlier in the oil fields, hole enlarging operations were conducted while drilling by the use of symmetrically designed underreamer or pump pressure-activated flip-arm underreamer or bi-center bits. [17]. Hole enlarging while drilling has been a proven method in the oil & gas industry in terms of cost saving and effectiveness [83].

For mining the narrow veins through drilling, first, a pilot hole is drilled through the center of the vein followed by a hole enlarging operation where a larger diameter hole is drilled by following the path of the pilot hole. A bull-nose with the hole opener drill bit is put in place to follow the path of the small-diameter hole.

In rotary drilling, the key goal is to construct the well in less time with a high rate of penetration (ROP) by the optimization of drilling conditions: WOB, rotary speed, flow rate, etc. There are a lot of factors to be considered when evaluating the drilling performance or ROP. In addition, mechanical specific energy (MSE) is commonly used to characterize the drilling performance. Higher ROP and lower MSE are the indicators of better drilling performance.

Cuttings generated from drilling operations work as a good indicator of drilling performance. Weichert (1991) identified that drilling mechanism and drilling conditions have a direct relation with particle size distribution (PSD) of the cuttings [5]. Particle size, shape, and mineralogical data can present real-time estimation of performance. In the arena of drilling engineering, particle size distribution can be applied to derive drilling performance in terms of rate of penetration. Several researchers have investigated the relationship between particle size and drilling performance and concluded that higher ROP produces coarser particles [73].

This paper focuses on studying mechanisms of hole widening drilling process in comparison to pilot hole drilling. Specifically, drill-off tests were conducted on hard rock, and the relationship between cuttings particle size and ROP which eventually leads to connecting with other drilling parameters were evaluated.

4.3 Terminology

4.3.1 Mechanical Specific Energy (MSE)

Mechanical Specific Energy or MSE is generally defined as the amount of energy required to excavate a unit volume of rock. It is expressed in psi or N/m^2 or Pascal. Teale (1964) invented the methodology to calculate MSE to evaluate drilling performance. He proposed the excavation be done by using two components of drilling: i) indentation and ii) rotation. His MSE equation is based on the combination of these two components. Teale's equation for MSE is as follows [66]:

For thrust components, Specific energy = $\frac{\mathrm{WOB}}{\text{Area of excavation}}$

For rotary components, Specific energy = $\frac{2\pi * \mathrm{RPM} * \mathrm{Torque}}{\text{Area of excavation} * \mathrm{ROP}}$

By combining these two equations, we get,

$$\mathrm{MSE} = \frac{\mathrm{WOB}}{A_B} + \frac{120\pi * \mathrm{RPM} * \mathrm{TOB}}{A_B * \mathrm{ROP}} \quad (4.1)$$

Where,

MSE = Mechanical Specific Energy, (Pa)

RPM = Revolution per Minute, (rpm)

A_B = Area of Bit, (m^2)

ROP = Rate of Penetration, (m/hr)

TOB = Torque on Bit, (N-m)

WOB = Weight on Bit, (N)

In 1992, Pessier and Fear introduced a bit specific coefficient of sliding friction (μ) to express torque as a function of WOB. They introduced this coefficient because most of the field data generated were WOB, RPM, and ROP. In the field, this Bit specific coefficient (μ) is assumed 0.5 for drag bits and 0.25 for tri-cone bits [84].

$$\mu = 3 * \frac{T}{D_B \ * WOB}$$

Thus,

$$T = \frac{1}{3} * \mu * D_B * WOB \ \text{(SI Unit)} \qquad (4.2)$$

By putting, the value of Eq. (2) in Eq. (1) produces,

$$MSE = \frac{WOB}{A_B} + \frac{160 * \mu * RPM * WOB}{D_B * ROP} \qquad (4.3)$$

Dupriest and Koederitz in (2005) presented a mechanical efficiency factor to adjust Teale's original MSE equation for field operation. They observed that MSE could be adjusted in the field to produce a value closer to rock strength to help drilling rig personnel to estimate the founder point, by multiplying the calculated MSE with the mechanical efficiency factor (EFF_M). From field data, they found that operators used 0.35 as EFF_M regardless of bit type or WOB. MSE is one of the most important parameters to analyze drilling efficiency [85]. In most cases, MSE remains much higher than the strength of rock. In the most efficient case, MSE value equals rock strength.

4.3.2 Weight on Bit (WOB) and Rate of Penetration (ROP)

The Weight on Bit (WOB) is used to provide a downward force to break the rock. It is measured in kN. The indentation that is done in drilling is due to the weight provided on the bit. The WOB is a basic input parameter for drilling rock and for drilling optimization. By using the optimum WOB, this can greatly increase the rate of penetration and decrease overall drilling time and cost.

Rate of Penetration is an output parameter that generates during drilling certain depths with varying WOB and RPM. ROP is measured in m/hr. ROP can be affected by different parameters like WOB, RPM, lithology, bit hydraulics, bit wear, and bit balling. Optimization of ROP is the most important factor to generate higher efficiency of drilling

4.3.3 Drilling Efficiency

In general, efficiency is a measurement of the productive output of a system for a given matrix of inputs. Drilling efficiency can be defined as "the construction and delivery of a useable well, while achieving the operational conditions needed to achieve the lowest cost imprint" [86]. It increases when ROP increases and declines with reduced ROP. Drilling efficiency is evaluated by correlating MSE with the strength of the formation being penetrated.

$$DE = \frac{CCS}{MSE} * 100\% \qquad (4.4)$$

Where, CCS = Confined Compressive Strength of rock

4.3.4 Drill-off Test (DOT)

Drill-off Test is an experimental method invented by Lubinski in 1958 to determine optimum ROP as a function of WOB [87]. It has been using in lab scale for the last 60 years for estimating and optimizing drilling performance. For designing a proper DOT, depth to be drilled and the changing rate of WOB are needed to be planned prior of the experiment [88]. Different tests have been conducted in different rock formations with varying WOB and RPM, and the result in ROP is plotted on a Cartesian graph as a function of WOB. Three regions are identified from ROP vs WOB Graph: i) Inadequate Depth of Cut (DOC), ii) Efficient drilling and iii) Inefficient drilling [85]. Region I is identified when the breaking of rock is not performed because of low WOB. After certain WOB, depth of cut increases and ROP increases efficiently. This efficient drilling region is marked as Region II. Region III is defined as the founder point after which ROP tends to decrease with increasing WOB. This portion is an inefficient drilling part where most of the energy is consumed for crushing and grinding of the particles below the bit. This can be caused by inefficient hole cleaning, bit balling, excessive vibrations, insufficient torque that leads to bit damage. An example of DOT graph is shown in fig 33.

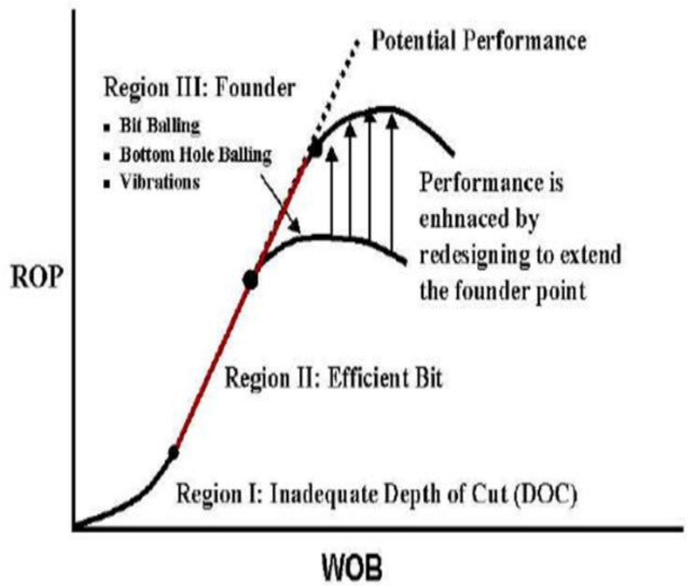


Figure 33: Drill-Off test (DOT) graph showing ROP as a function of WOB [86].

4.4 Experimental Setup

4.4.1 Drilling System

In the Drilling Technology Laboratory at Memorial University of Newfoundland, a Small Drilling Simulator (SDS) is in place to conduct different types of drill-off tests. This drilling simulator can generate 300 and 600 rpm and different WOB by using suspended mass plates from a wheel. Tap water is used to flow into the bit and get the cuttings out of the drill hole through the annulus. A laser sensor is installed in the system to acquire the readings of RPM during operations. Torque on Bit is calculated by using the values of motor speed and motor current.

For performing drilling operations in hard rock, a block of quartz was used. The UCS of the rock is about 133.3 MPa. Cement slurry was used to make the quartz block suitable and stable for drilling in SDS. Fig 34 illustrates the small drilling simulator and cutting collection system that were used for drillings.

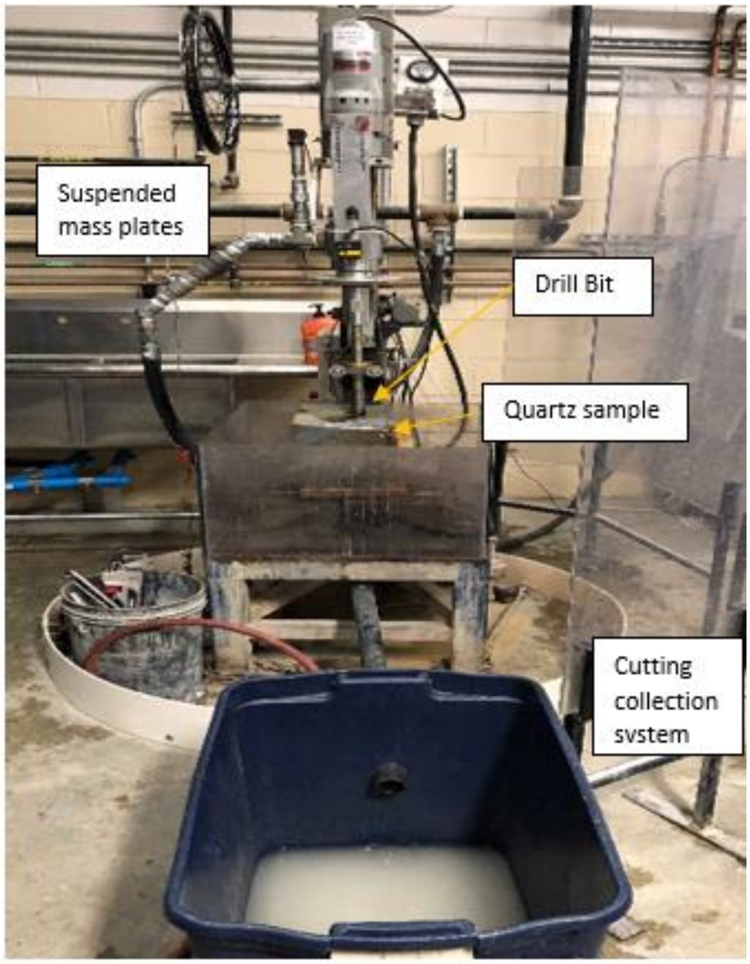


Figure 34: Small Drilling Simulator (SDS) with cutting collection system

4.4.2 Experimental Plan

A proper experimental plan was executed to do the experiments. For pilot hole drilling, coring bit and PDC bit were utilized, and for HWD only PDC bit was used.

In this study, three types of drillings were investigated: coring bit drilling, PDC bit hole widening drilling and PDC bit pilot hole drilling. The coring bit drilling was completed using a 26.4 mm diamond coring bit and based on this existing hole, hole widening drilling was conducted using a 32.4 mm PDC bit. As a comparison, the PDC bit was used to drill pilot holes, which is referred to as PDC bit pilot hole drilling. Fig 35 below demonstrates three separate types of drilling operations that were performed for investigation.

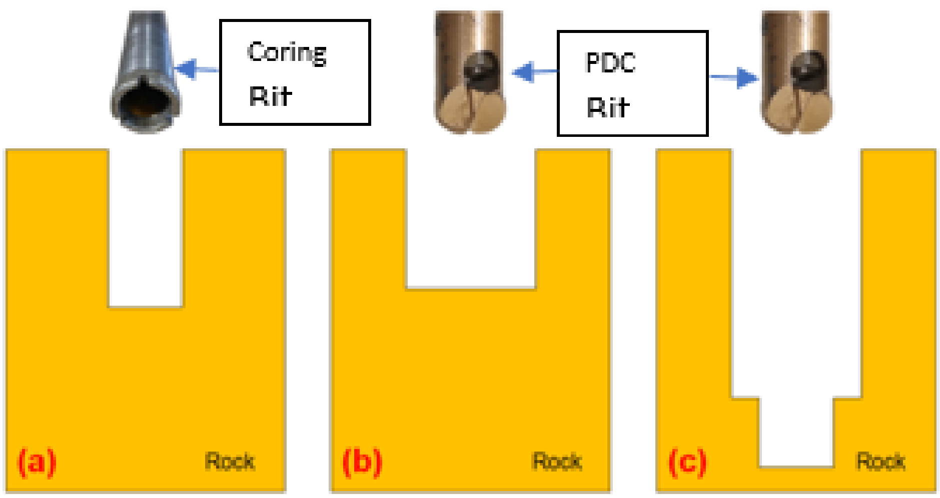


Figure 35: (a) Coring bit drilling of 26.4 mm diameter, (b) Pilot hole drilling with PDC bit of 32.4 mm diameter, (c) HWD with PDC bit of 32.4 mm diameter on the existing 26.4 mm diameter hole

Table 5: Experimental Plan for this study

Experiment	Bit	Diameter	WOB (KN)	RPM
Pilot Hole	Coring	26.4 mm	1.2348	300
Pilot Hole	Coring	26.4 mm	1.5738	
Pilot Hole	Coring	26.4 mm	2.0325	
Pilot Hole	Coring	26.4 mm	2.1697	
Pilot Hole	Coring	26.4 mm	2.3183	
Pilot hole and HWD	PDC	32.4 mm	1.2348	
Pilot hole and HWD	PDC	32.4 mm	1.5738	
Pilot hole and HWD	PDC	32.4 mm	2.0325	
Pilot hole and HWD	PDC	32.4 mm	2.1697	
Pilot hole and HWD	PDC	32.4 mm	2.3183	

Fig 36 shows the two-stage drilled hole in the quartz block after the experiments. To study drilling behaviors with various WOB, five (05) different WOB were used during drilling operations for coring drilling, pilot hole drilling with PDC bit and hole widening drilling with PDC bit. These WOB were applied to a bit by using suspended mass plates from the wheel attached to SDS. Table 5 above summarizes the experimental plan for the study.

4.4.3 Particle size analysis Method

The cutting collection system was installed with the drilling simulator. The inlet of the collection system was attached to the outlet of the drilling system. The water coming out from the SDS containing all the cuttings passes through the collection system and cuttings were collected after each experiment. After each run, the water was flushed out from the system to ensure proper cleaning and collection. ASTM standard D6913-04 (ASTM 2009) and D422-63 (ASTM 2007) were followed to analyze particle size distribution for the cuttings that are bigger or less than 75 µm which are called sieve analysis and hydrometer analysis, accordingly [41, 45]. Cutting collection procedure from researchers of DTL was followed for proper collection and preparation of cuttings [6, 57].

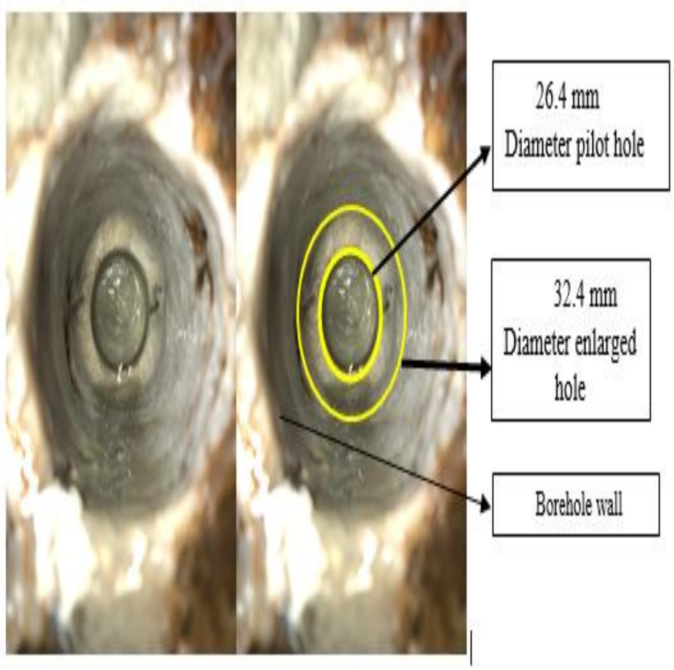


Figure 36: Image of the two-stage drilled hole in quartz rock block

After collection, cuttings were put in the oven for 12-14 hours and dried at the temperature of 60-70 degree Celsius. After fully dehydrated, an automated sieve shaker was used to separate different sizes of particles and the weight of each sieve was considered for particle size analysis. Different sizes of cuttings were sieved with mesh sizes of 2 mm, 850 micron, 630 micron, 315 micron, 250 micron, 150 micron, and 75 micron.

Figure 37: Cuttings preparation and Sieve analysis

After sieve analysis, a small percentage of cuttings were found in a smaller size range, and for the details analysis of the cuttings hydrometer test was performed. Sodium Hexa-metaphosphate was used as a dispersion agent and different readings were collected for proper measurement of the particle size. Fig 37 and 38 are presenting the process of sieve analysis and Hydrometer analysis for generating particle size distribution. Using all the particle size generated from both the sieve test and hydrometer test, the cumulative weight percentage was plotted against the size to demonstrate the particle size distribution of the cuttings.

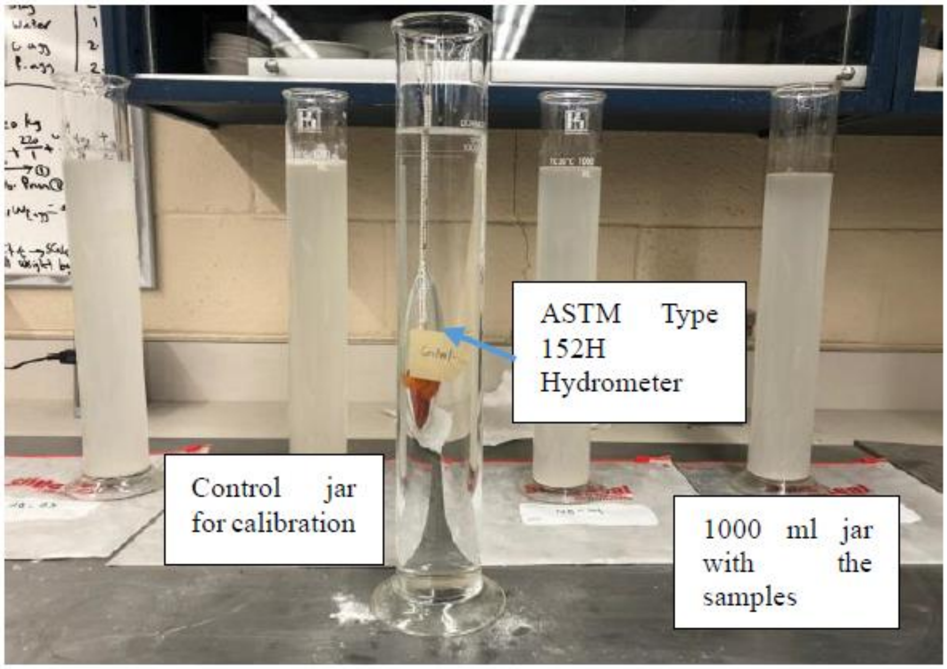


Figure 38: Particle size analysis less than 75 μm using hydrometer

4.5 Drilling Performance Analysis

Drill-Off Tests were conducted on quartz block with several different WOB and 300 RPM. Data was being collected continuously to determine the relationship between input and output drilling parameters by built-in software. Cuttings were also amassed with a proper system to relate parameters to cutting size. For this study, 15 sets of drilling operations were carried out with different types of bits.

4.5.1 Results from Drill-Off Tests (DOT)

Drilling data that was generated throughout the time of tests, an extensive analysis was performed to evaluate parameters. Graphs were constructed to get information about ROP, RPM, and torque. Figure 39 shows graphs of depth vs time, vibration vs time and motor current vs time for an individual bit and WOB.

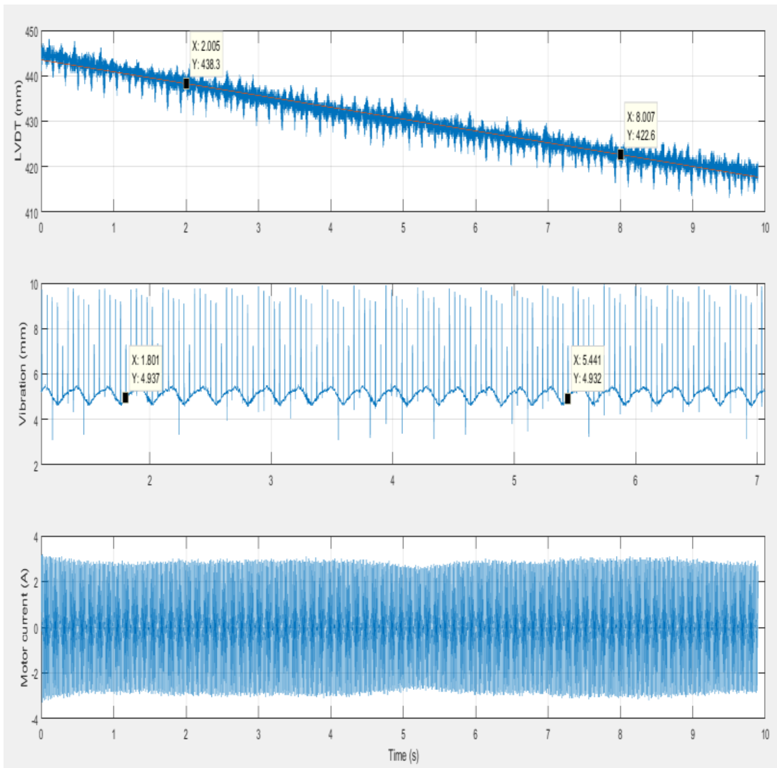


Figure 39: Graphs for calculation of ROP, Rotary speed, and Torque

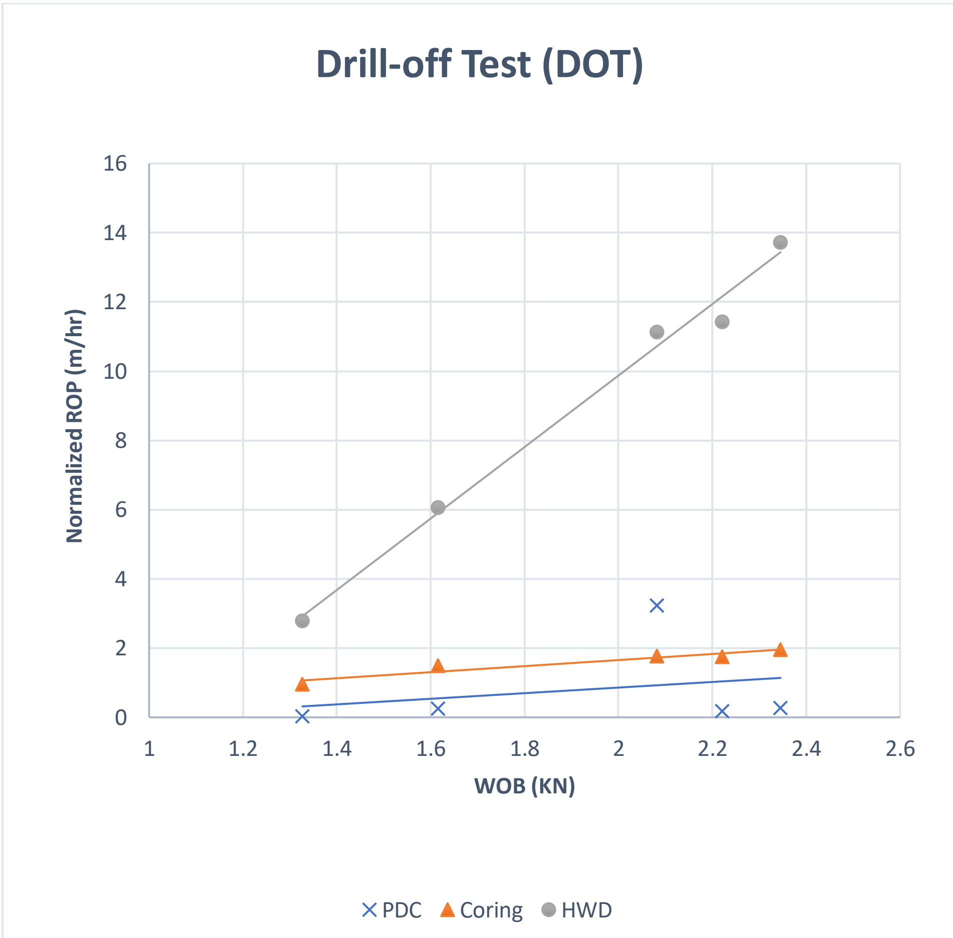


Figure 40: Normalized ROP (to remove the effect of rpm less than 300) as a function of WOB

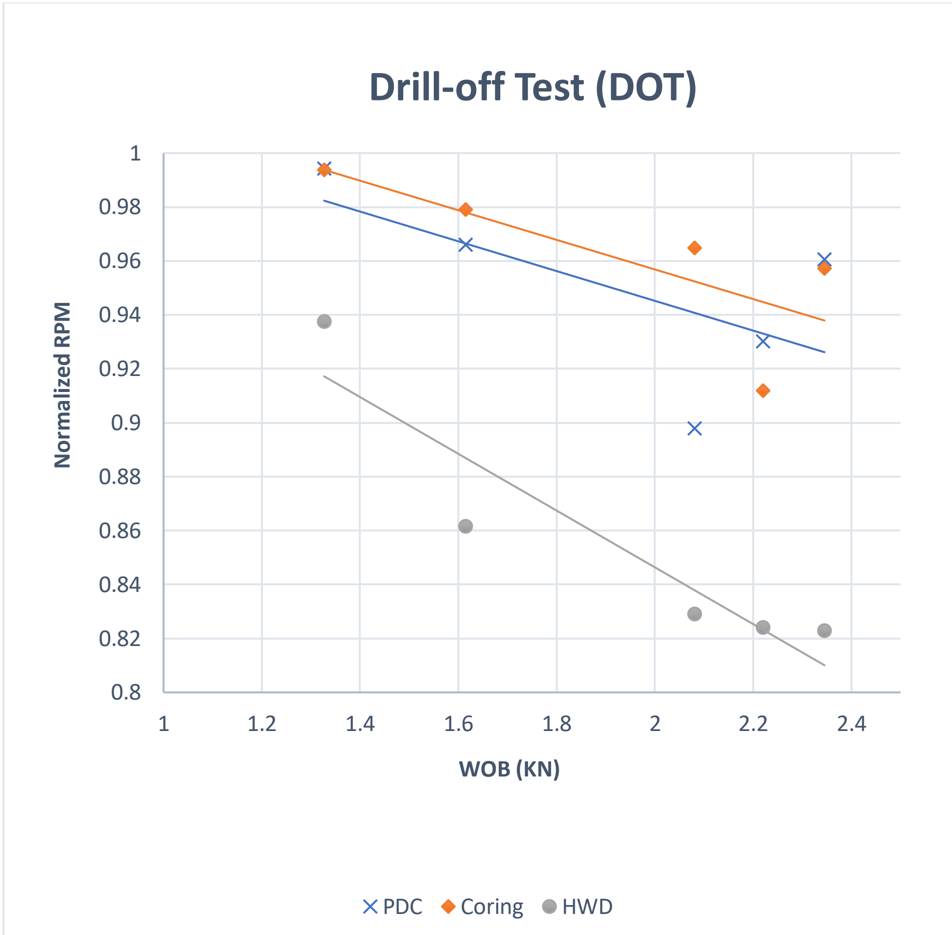


Figure 41: Normalized resulted RPM generated by the drilling system as a function of applied WOB

It is worth mentioning that in the course of drilling experiments rotary speed actually generated by SDS motor was not perfectly 300 rpm. Because of restrictions imposed by torque and vibration, real resulted RPM was lower than 300. However, for the elimination of the effect of lower RPM on ROP, normalization of both ROP and resultant RPM was completed. Normalization of the ROP was performed by using the actual rate of penetration times the fraction of rated rotary speed over the actual rotary speed. And normalized resulted rotary speed was calculated from the ratio of actual rotary speed over the generated rotary speed of the system [78]. Figures 40 and 41 show the results of Drill-Off Tests in terms of normalized ROP and normalized resulted rotary speed.

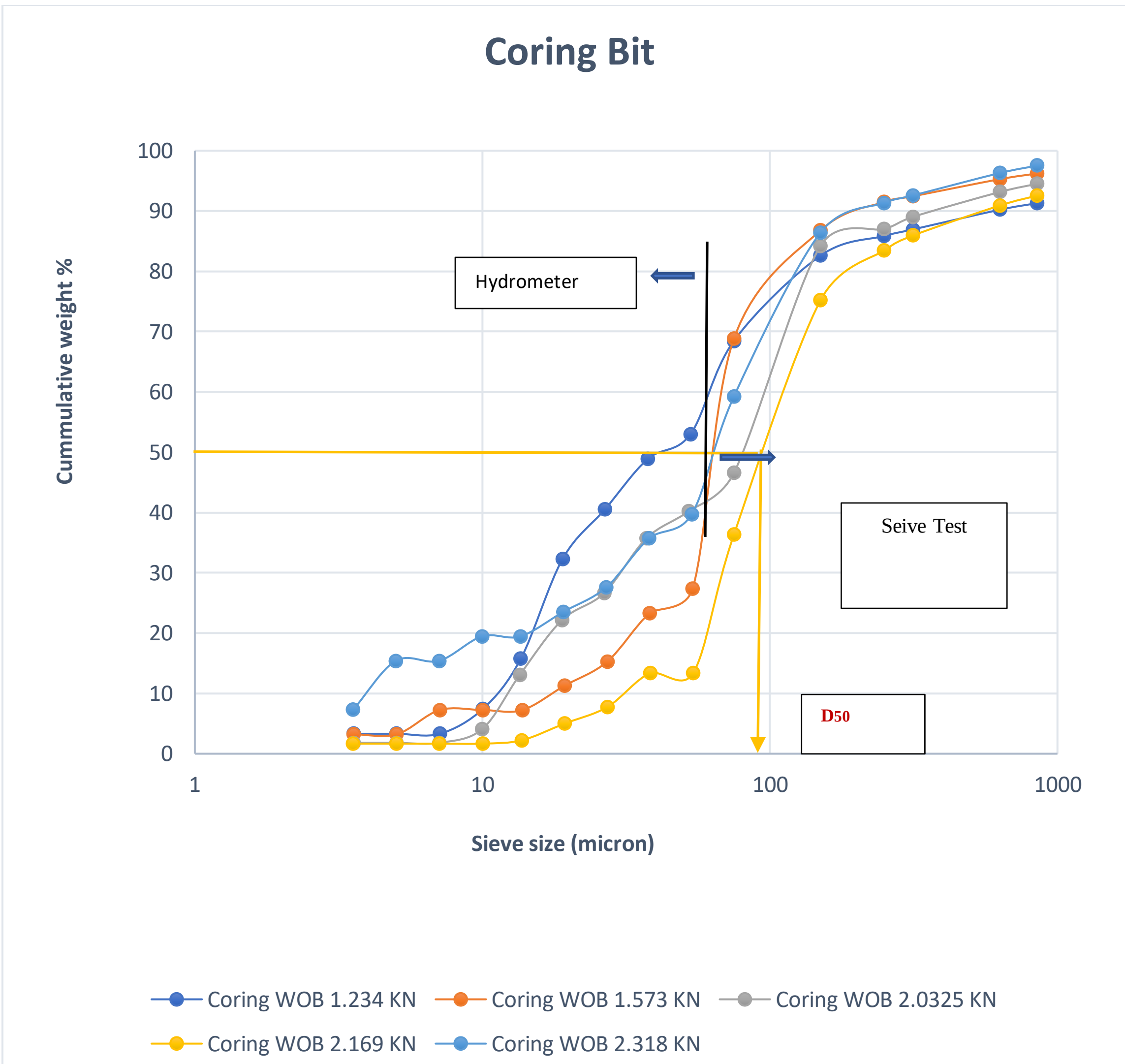
In hole widening drilling (HWD) operation, the rate of penetration remains higher with various WOB than any other setup. It shows that ROP increased incrementally at a good rate as WOB increased. For pilot hole drilling, ROP shows a kind of similarity for both PDC bit and coring bit. Earlier, it was found that for HWD, it produced higher ROP despite the poor response of PDC bit in hard rock formation [78]. In general, the PDC bit does not perform well in terms of drilling performance in the rock that possesses higher strength.

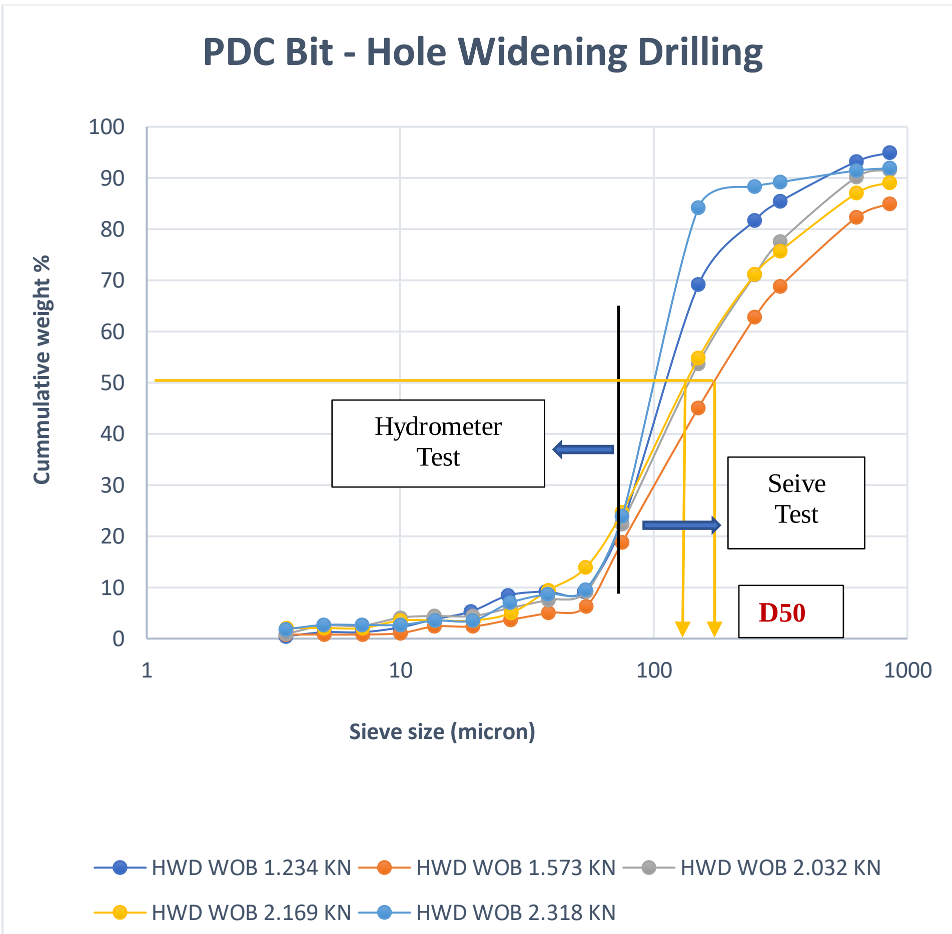
Pilot hole drilling operations with PDC and coring bits resulted in higher RPM compared to HWD. Lower rotary speed and higher ROP is a well-known trend of better drilling performance. This phenomenon was found from the Drill-Off Tests of the hole widening operation. Although the PDC bit is not an acceptable performer in hard rock drilling, it shows remarkable attainment during HWD operation in unfavorable conditions.

4.5.2 Results from Particle Size Distribution

The major function of particle analysis is to generate quantitative data related to the size and size distribution of the particles. Test sieving is a commonly used method for particle size analysis. A wide range of particle sizes can be found from test sieving. Sieve analysis is accomplished by passing a known weight of sample through finer sieves and weighting the mass of each sieve to determine the accumulated percentage weight. Then the results can be presented in several methods, through graphs or diagrams, but the most popular method is the Particle Size Distribution (PSD) diagram. In this method, the cumulative percentage of oversize or undersize particles is plotted against the particle size in micron in a semi-log graph.

For this study, PSD diagrams are plotted for coring bit drillings, pilot hole drilling with PDC bit and HWD operation with PDC bit. Demonstrations of PSD diagrams for various drilling settings and input parameters are in Figure 42.




PDC Bit - Hole Widening Drilling
Cummulative weight %
100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
Sieve size (micron)
Hydrometer Test
Seive Test
D50
HWD WOB 1.234 KN
HWD WOB 1.573 KN
HWD WOB 2.032 KN
HWD WOB 2.169 KN
HWD WOB 2.318 KN

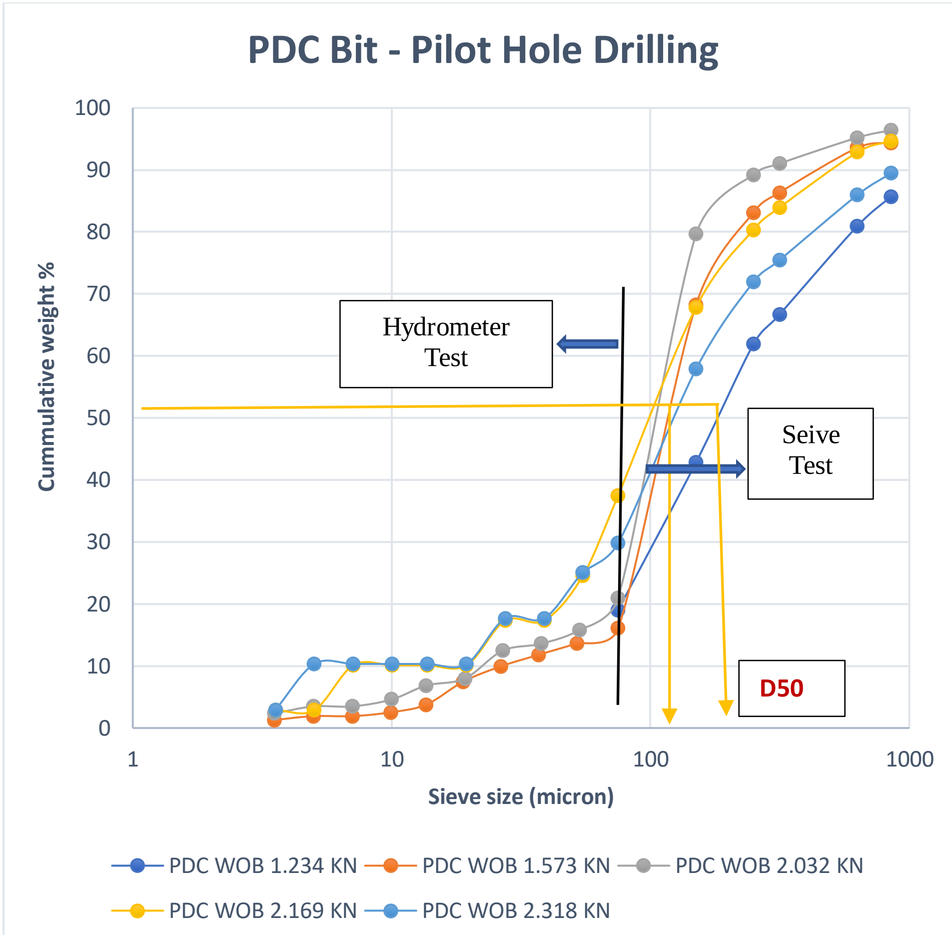


Figure 42: Particle Size Distribution (PSD) diagrams for different drilling conditions and parameters

It was observed that the HWD operation produces approximately 80% particles that are bigger than 75 micron in size. In contrast, the same PDC bit for pilot hole drilling generates on average 68% particles bigger than 75 micron and coring bit produces the finest ones. D_{50} values of particle size distribution diagrams were also found to be bigger for HWD than two other drilling operations. This data supports the fact that higher WOB accompanied by higher ROP produces bigger sized particles. However, this does not verify that PDC bit is a better option to drill harder formations in HWD as particle size distribution does not fully match with the concept of ‘higher WOB produces bigger particles.’ Fig 43 shows D_{50} values of different particle size distribution with respect to WOB.

It was found that D_{50} values for hole widening drilling and pilot hole drilling with PDC bit were bigger comparing to coring bit drilling, whereas median particle size decreased with increased WOB for drilling with PDC bit.

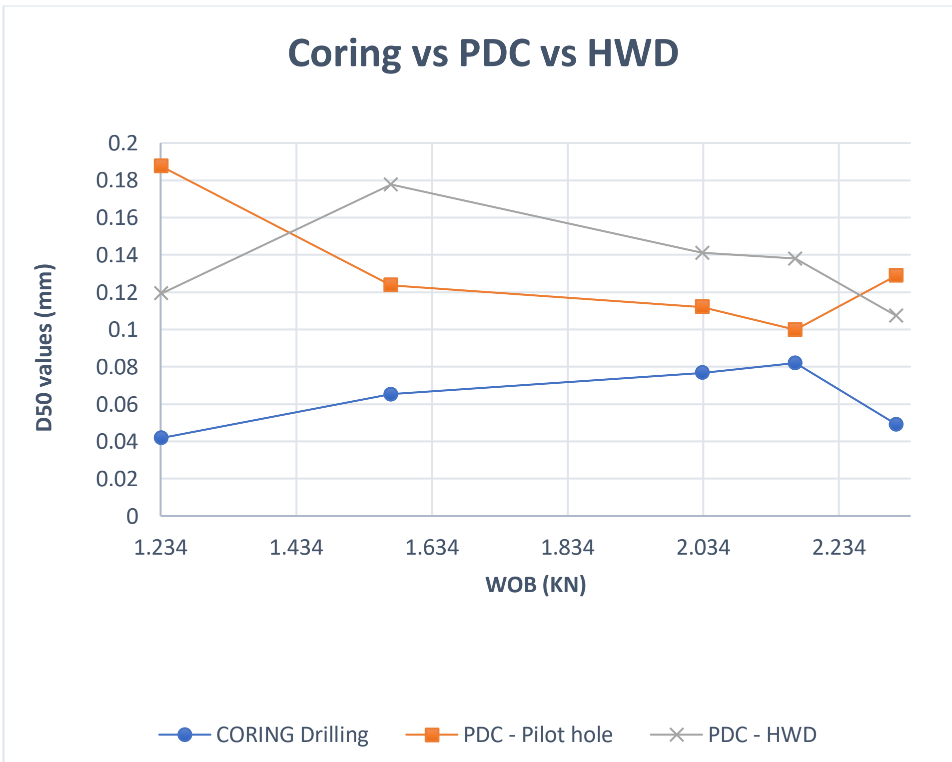


Figure 43: D50 values of PSD of cuttings with respect to different WOB for three types of drilling

An investigation was also accomplished to see PSD with different drilling conditions but the same WOB. Despite a couple of cases, it was found that HWD operation always produces larger particles. Figure 44 - 47 below illustrate the relationships.

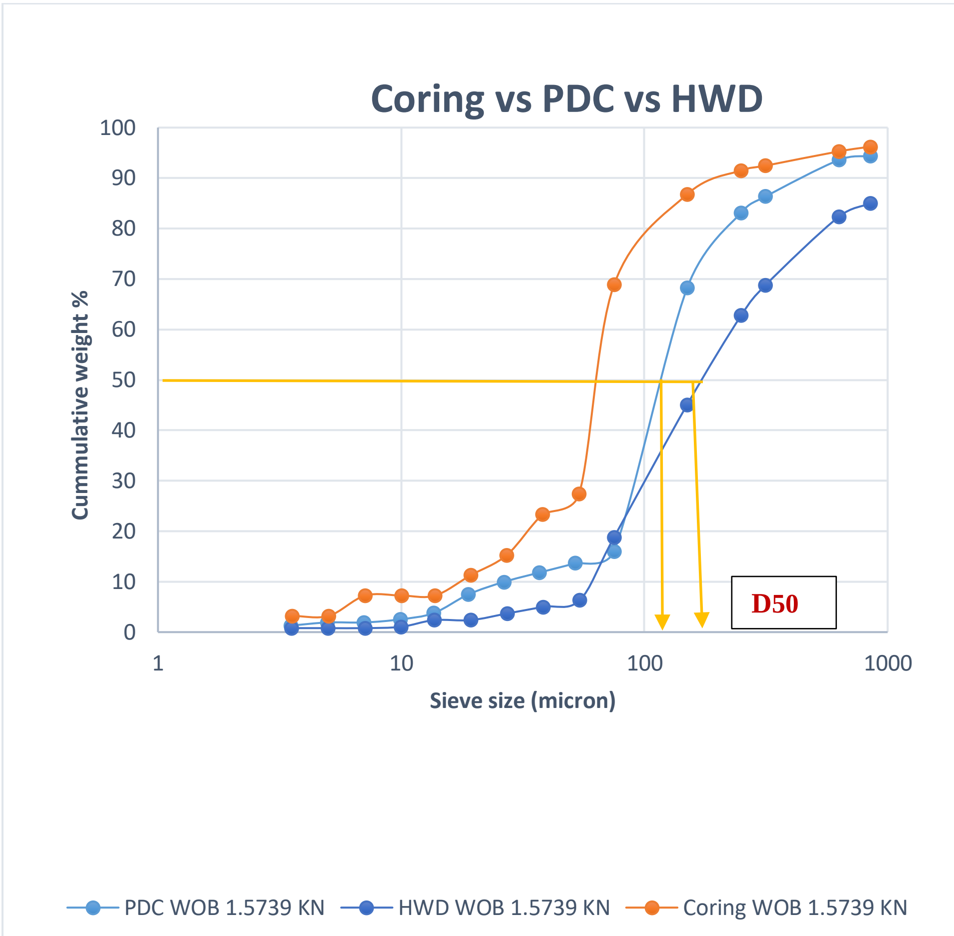


Figure 44: PSD diagrams comparing different drilling settings and showing D50 values for 1.575 kN WOB

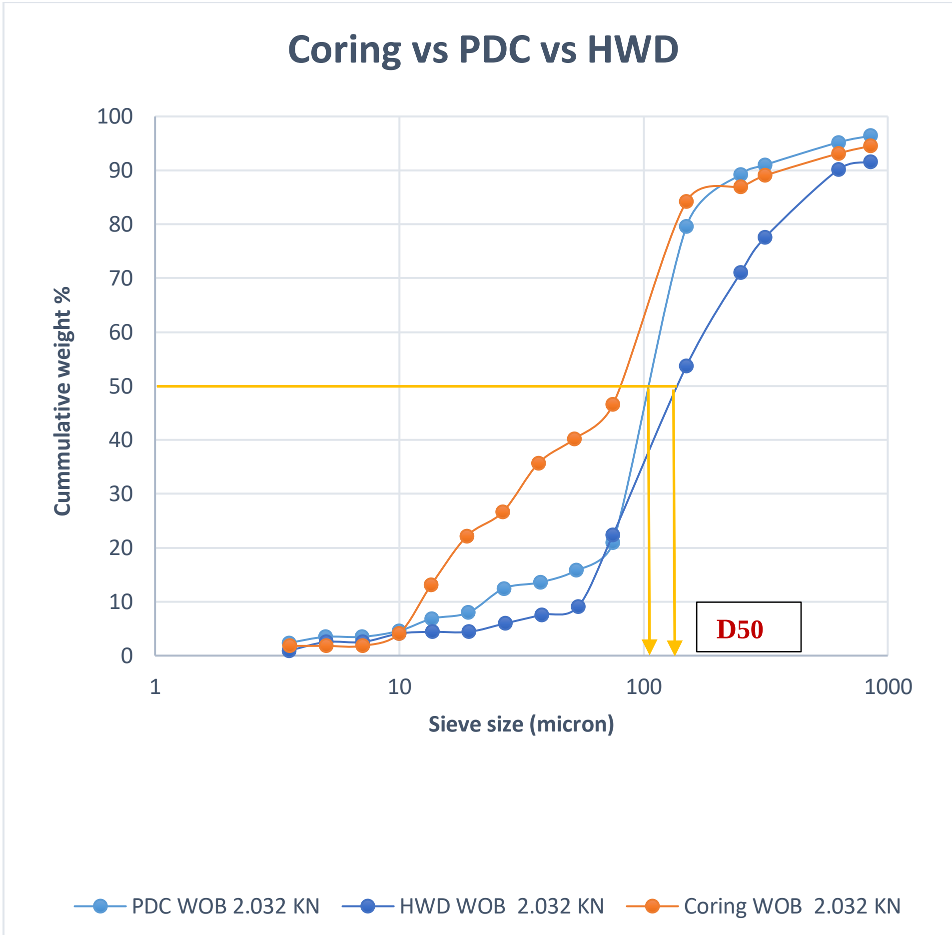


Figure 45: PSD diagrams comparing different drilling settings and showing D50 values for 2.032 kN WOB

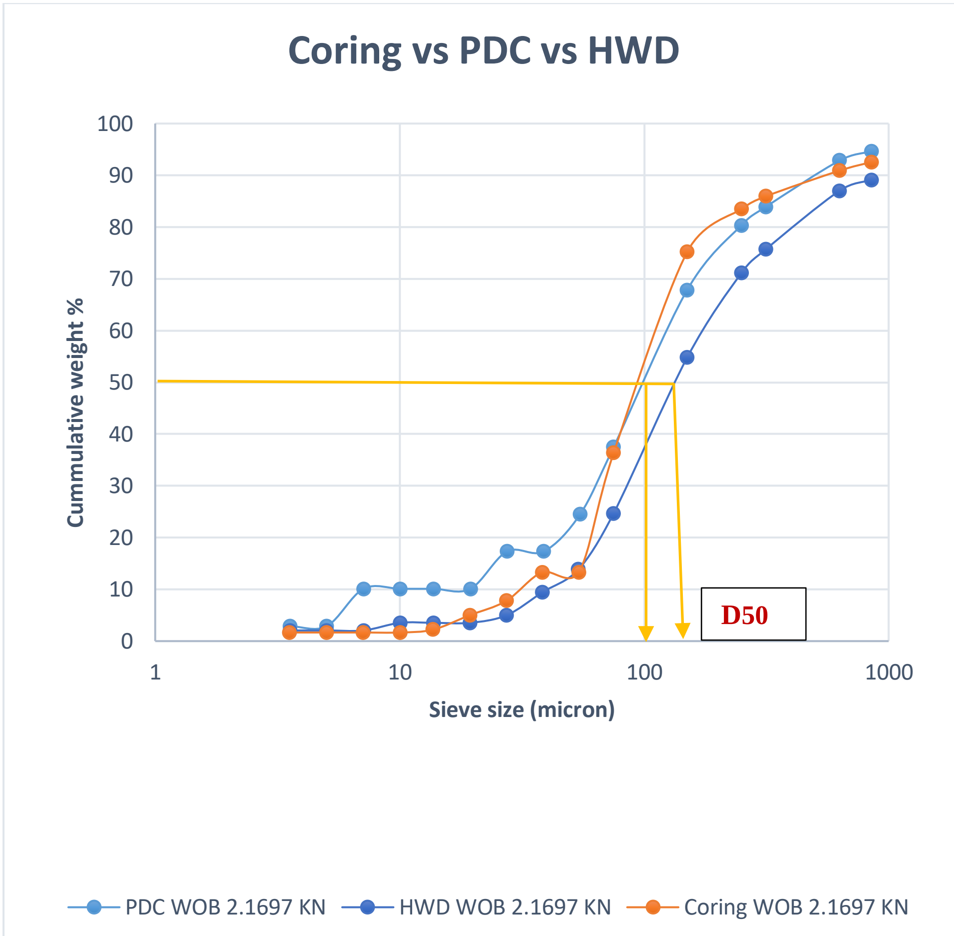


Figure 46: PSD diagrams comparing different drilling settings and showing D50 values for 2.169 kN WOB

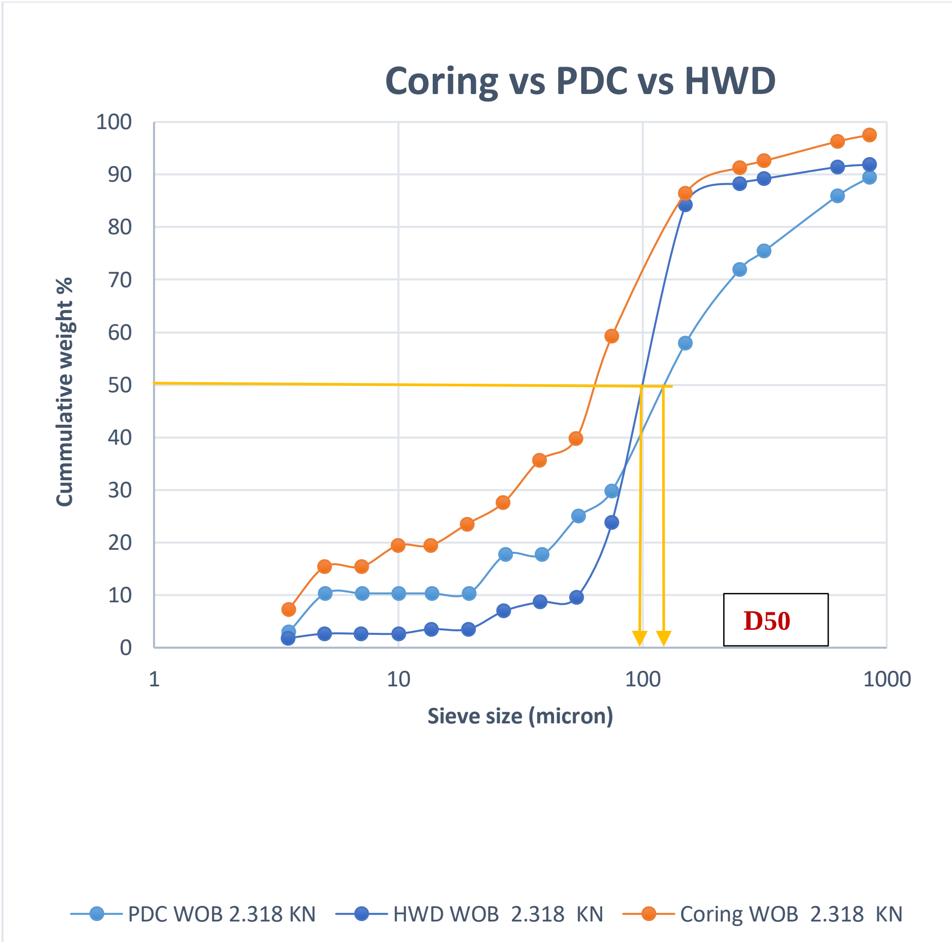
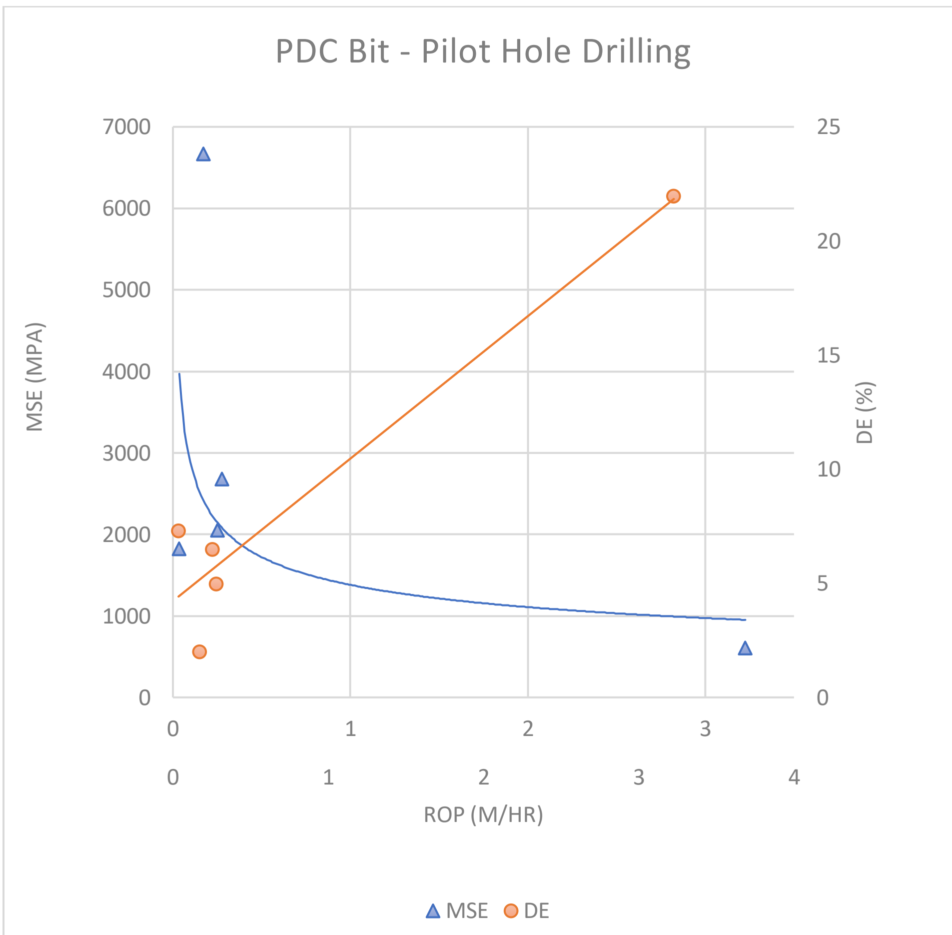


Figure 47: PSD diagrams comparing different drilling settings and showing D50 values for 2.318 kN WOB

In all conditions, HWD generates bigger particles than the other two for the same WOB. In the case of 2.318 KN, the result does not comply with previous trends. This can be triggered by internal fractures of the rock that leads to crushing or grinding of the particles.

4.5.3 Results from MSE

MSE calculation has become an important tool to analyze the performance of drilling operations. Drilling efficiency and bit performance enhancement analysis can be greatly supported by MSE values. In industry, MSE values are being applied to drilling optimization, identifying drilling problems and pore pressure predictions [89].



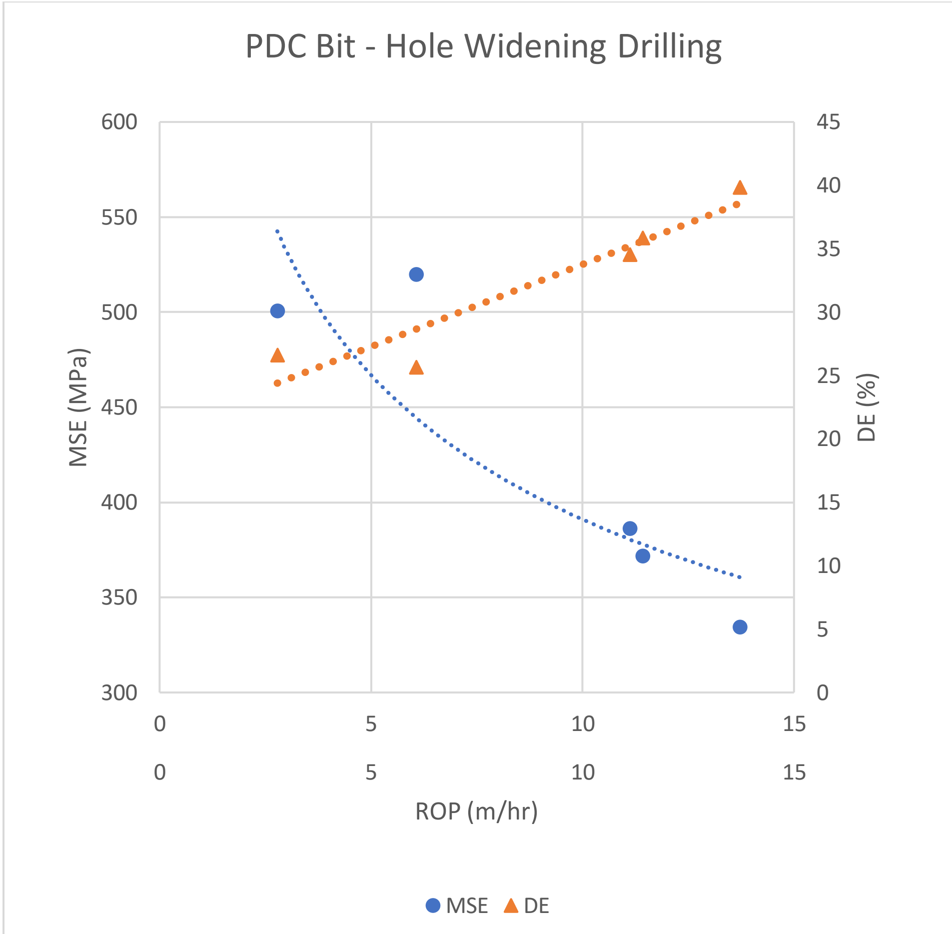


Figure 48: Graph showing MSE, DE as a function of ROP

In this study, MSE was calculated by using drilling parameters generated by the simulator in real-time. Figure 48 shows MSE as a function of ROP for pilot hole drilling with PDC bit and HWD. This MSE was calculated by using equation invented by Teale (1965) [66].

From the graphs (fig 48), it is evident that hole widening operations consume less energy compared to conventional drilling. Even though a PDC bit is not a good performer in hard rock like quartz it showed better results for hole widening than pilot hole drilling. The average MSE required for a hole widening operation is approximately 420 MPa whereas for pilot hole drilling it is ~2800 MPa.

Such findings better support the interaction between MSE and ROP. In the lab-scale experiments, it is seen that for hole widening drilling, ROP is higher than any other operation. If ROP increases, MSE decreases as MSE is inversely proportional to ROP. Therefore, it is apparent that the hole widening operation required less energy.

Drilling Efficiency (DE) was also calculated for the investigation. It was observed from experimental results that the efficiency of HWD quantitatively remains much higher compared to pilot hole drilling with the same drilling conditions and parameters.

4.6 Conclusion

Hole widening drilling achieves a higher rate of penetration than other operations in the same type of rock and with the same drilling input parameters. Cutting sizes were also found to be coarser for HWD operation from PSD diagrams.

In the case of higher WOB cutting size did not follow the style, it can be attributed to regrinding of the particles due to the internal fracture of the rock that was triggered by successive drilling. Sometimes, the internal structure of the rock may lead to a false interpretation of the drilling performance and efficiency. Proper hole cleaning and the collection of cuttings are also crucial factors to do an accurate analysis of the cuttings and evaluate drilling performance.

MSE works as a very good drilling efficiency indicator. With higher ROP, MSE results in a lower value, hence increasing the drilling efficiency. From this study, it is evident that

HWD produces higher ROP value while consuming lower energy that results in better efficiency.

Experimental data showed that the system was operating in in-efficient conditions throughout the drilling operations for both pilot hole and hole widening operations. Such results indicate that both mechanical and bit hydraulic related components are vital for MSE calculation.

Chapter 05: Design and Implementation of a Laboratory Based Drill Cuttings Collection System

This chapter discusses the design and fabrication of a cutting collection system that can be installed and used in the Drilling Technology Laboratory (DTL) at Memorial University of Newfoundland. The design was based on the experimental data generated during various Drill-off Tests conducted in the DTL.

5.1 Introduction

In every drilling operation, the use of drilling fluid is mandatory. This fluid is circulated from the surface through the drill string and bit to the downhole and return to the surface through the annulus with drill cuttings as solid particles. Drilling fluid is used for many vital purposes in drilling operations and one of these purposes is to remove the drill cuttings from the bottom of the hole and release them at the surface for proper maintenance of the drilling fluid properties. The solids that come up to the surface with drill fluids play a negative role in maintaining the drilling fluid characteristics. The importance of removal of solids has been studied by experts and established by field and laboratory studies over the last 70 years [90, 91, 92].

Solids generated during drilling operation are small particles of the rock that is being drilled. These particles are referred to as drill cuttings and they have a vital role in predicting drilling performance in terms of the rate of penetration. Drill cuttings are used to generate lithological stratigraphy of the subsurface while drilling formations at different depths. These cuttings are also used to produce mineralogical data of the rock formations. Drill cutting particles or solids that emerge in the drilling fluids are separated from the drilling mud which can be investigated to evaluate drilling performance by performing lab based or field scale particle size analysis. Researchers have investigated and established a direct relationship between different drilling parameters and particle size distribution as mentioned in the previous chapters 2, 3, and 4.

Drill cuttings generated during different Drill-Off Tests (DOTs) contain much information and these cuttings can be analyzed to evaluate drilling performance. Both pilot hole and hole opening drilling are under investigation in the DTL and many DOTs have been performed to investigate these drilling techniques [78]. Proper collection of the cuttings is very important for proper analysis. Solid control units for the drilling industry are used to remove the cuttings from the drill fluid. Upon studying the principles of a solid removal system used in field scale, the design of a laboratory based cutting collection system was produced. Data acquired from several Drill-Off Tests performed in the laboratory and analysis of the cuttings collected during drilling experiments were utilized to plan lab based cutting collection systems for a Small Drilling Simulator (SDS) and a Large Drilling Simulator (LDS) placed in the Drilling Technology Laboratory (DTL).

5.2 Solid control system used in drilling industry

Drilled solids are constantly incorporated into the drilling mud. While drilling is tolerable to some extent, it can affect the drilling rate, torque and drag, hole stability, bit balling, life of bits and pumps etc. Lower mud cost, better bit life and pump life, increased drilling rate, positive control of mud rheology, provide better mud cake and reduce filtration, and better borehole stability are results of controlling solids in the drilling fluid [91].

Solid removal equipment is used in the industry to remove drill cuttings from the drill mud returning from the borehole. It is basically designed to monitor and control the excessive deposition of solid in the mud system. Removal of solids on the rig site is performed by using one or more of the following techniques:

- Screening: Shale shakers
- Hydrocycloning: Desander, Desilter
- Centrifugation: Scalping and decanting centrifuges
- Gravitational settling: Sumps, dewatering units.

The efficiency of the solid control system depends on the perfect choice of equipment combinations for a particular situation. The arrangement of the equipment must be in the correct position with optimal engineering design and maintenance. In this system, each piece of equipment can handle a certain particle size range, which requires the system to incorporate several pieces of mechanical equipment that can effectively retain a wide range of particles from the drilling mud circulated from the borehole.

Shale shakers have been used in the industry as the most common screening device. Shale shakers in general incorporate all the mechanical equipment work on screening by means of shaking, vibrating and oscillating. Different sizes of meshes are employed for screening particles in shale shakers. Meshes are selected for the screen based on some factors such as particle shape, fluid viscosity, feed rates, and particle cohesiveness. Two types of shakers are found to be utilized for screening the particles. One is a standard shaker which deals with solids larger than 440 microns and a fine screen shaker that separates particles larger than 75 microns [91]. The particle separation done by the shale shaker is not simply separating particles larger than the mesh size but also has a high vibratory shaker speed that prevents some undersized particles from passing through the screen.

Hydrocyclones have been used in the industry for decades, and the size and shape needed in particular situations are determined by the specific sized particles that they are designed to remove. When the mud is processed by the shale shakers, mud is transferred to degassers to eliminate gas from the mud and then to the desander and the desilter for further treating [93]. The desanders and desilters are designed to remove particles the size of sand and silt, respectively. These hydrocyclones can handle particles ranging from 15 – 74 microns.

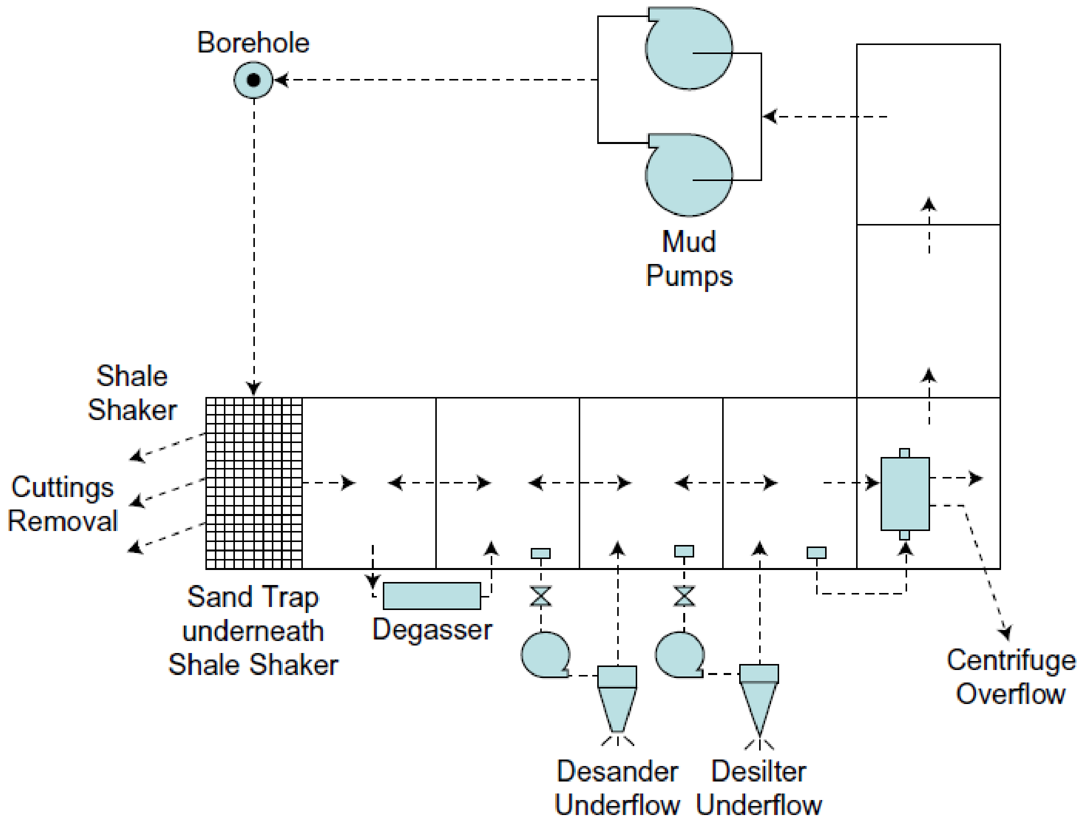


Figure 49: Schematic diagram of solid-removal equipment [94]

The decanting centrifuge is used to remove all free liquid portions of the drilling mud and leaves only the absorbed moisture on the surface area of the fluid. The use of a centrifuge eliminates the hole problems that are generated by a high concentration of colloidal solids.

5.3 Cutting collection system design for Small Drilling Simulator (SDS)

The Small Drilling Simulator (SDS) is a laboratory-based drill rig generally used for performing Drill-Off Tests (DOT) on various rock samples. This system comprises of a motor as rotary head, a loading system supported by a rack and pinion system, a fluid circulation system for proper cleaning of the bottom hole, and a data acquisition system. The rotary system is powered by an electric motor that can move vertically along the steel support and can deliver the maximum bit power of 4 kW. This system can generate rotary speeds of 300 RPM and 600 RPM. A constant WOB is provided on bit by the loading system. This system can generate a downward force by utilizing a rack and pinion system and a suspended weight. The fluid circulation system consists of a water tank and a triplex pump. The normal tap water circulation system can also be used during experiments. The system includes a swivel that creates a way for fluid to pass through the drill pipe and bit nozzles for cooling the bit and cleaning the bottom hole for better efficiency. The drill pipe connects the bit with the system for drilling holes [95]. For recording different drilling parameters, a set of sensors is also installed into the system. A linear variable differential transducer (LVDT) is installed in the system to monitor penetration depths of the drill bit [60] and a laser triangulation sensor is used to measure the relative displacement between the motor head and the drill pipe by reflecting a signal on a flat steel disk [57]. Figure 50 illustrates a schematic diagram of the setup.

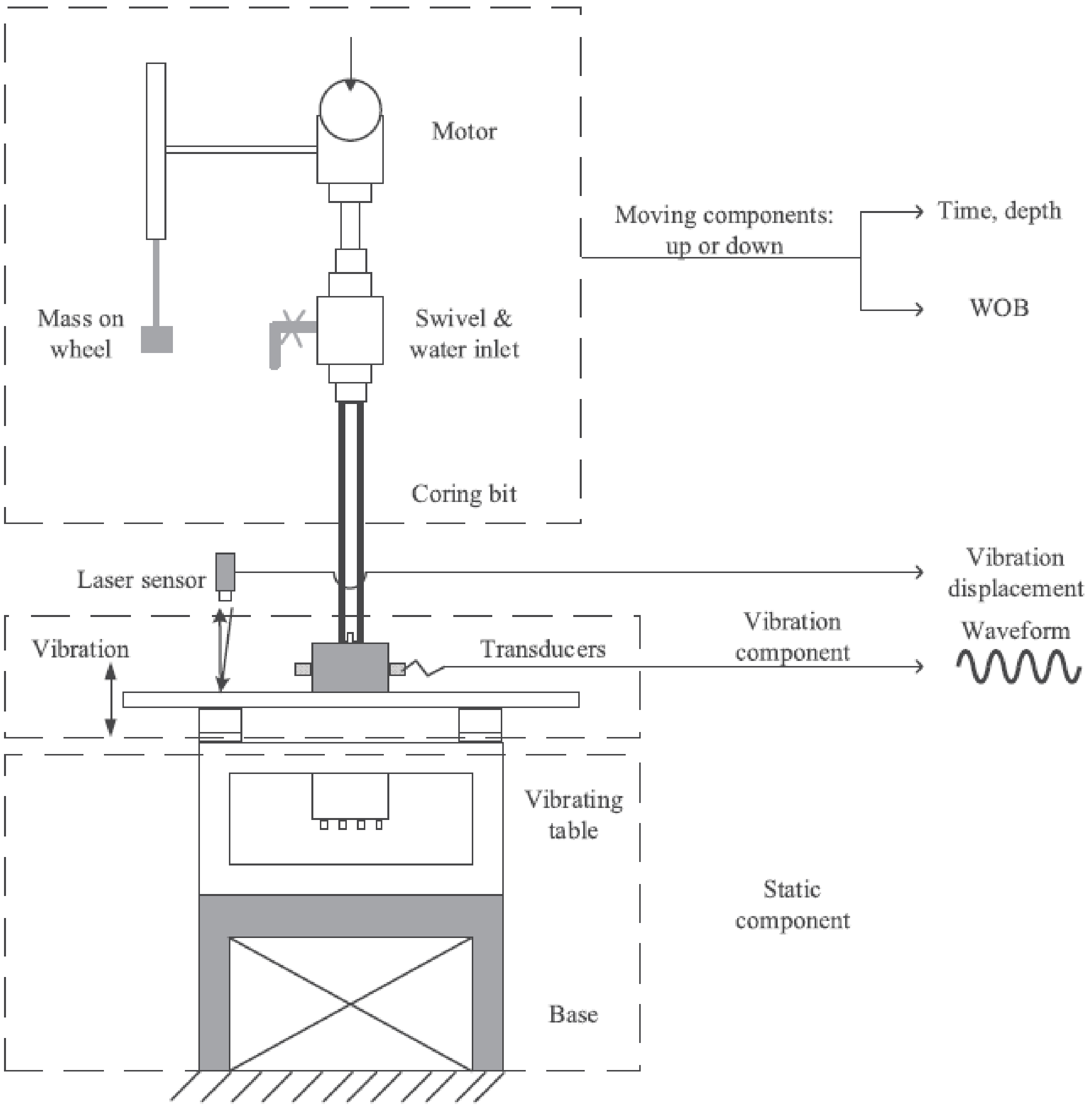


Figure 50: Schematic diagram of Small Drilling Simulator (SDS) at the Drilling Technology Laboratory (DTL) of Memorial University of Newfoundland [60].

The Small Drilling Simulator (SDS) can generate drill cuttings through drilling experiments that can provide a lot of valuable information to evaluate penetration mechanisms and drilling performances of pilot holes and hole widening drilling operations. Proper collection of cuttings is the foremost criteria to get the best drill cuttings data. Basic cutting collection systems for the design of the SDS were evaluated from the solid control system used in the drilling industry. A shale shaker is used to screen bigger particles from the mud that can then be cast-off to retain the cuttings from the drill fluid passing out of the SDS.

The installed cutting collection system is comprised of a water tank (23” Length x 16” Width x 13” Height) to carry the water coming out of the drilling system. An intel and discharge line connected to the water tank to get the water from the system and release the water after retaining of the cutting through the main discharge line. A modified test sieve of 8-inch diameter and 5-inch height with proper mesh or screen that can withstand a maximum fluid flow rate of 40 liter/min (fig 51). The modified test sieve is installed in the front face of the inlet line of the collection system through which water will pass by and leave the cutting bigger than the used mesh size (fig 52). After each drill run, cuttings can be collected from the modified mesh for further analysis.

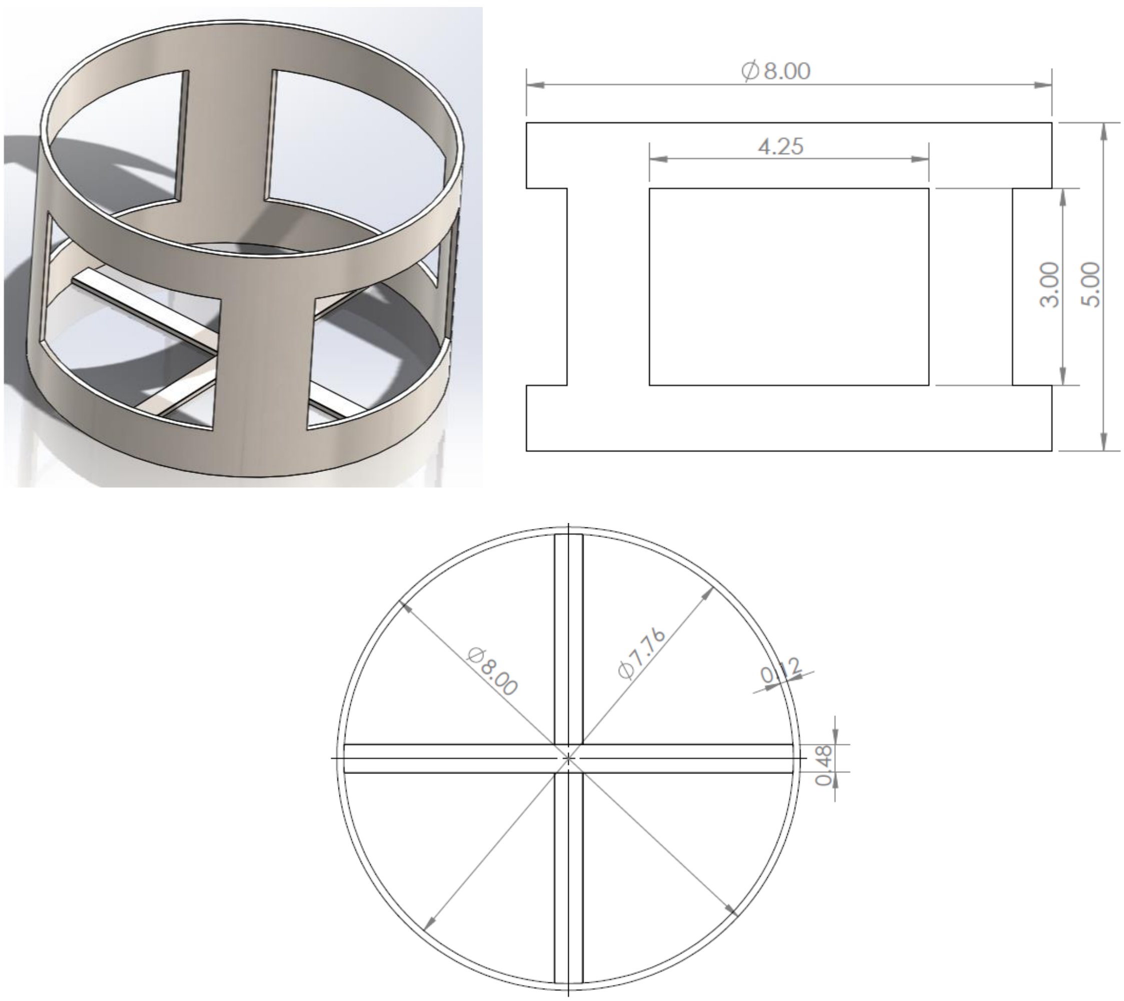


Figure 51: Design of the modified test sieve

Figure 52: SDS before and after the installation of cutting collection system

5.4 Cutting Collection System design for Large Drilling Simulator (LDS)

The Large Drilling Simulator (LDS) is a laboratory based physical setup that is designed to study drilling penetration mechanisms, the effect of vibration, bit wear, managed pressure drilling and drilling efficiency through a proper experimental plan and through experiments. To date, several DOTs have been conducted using this simulator to characterize drilling parameters for pilot hole drilling and hole widening drilling operations. Rotary system, WOB system, and drill cell and mud circulation system are three basic units that are used to evaluate the effect of drilling parameters. A 32-kW servo motor capable to generate 550 rpm to 1000 rpm make up the rotary system. Associated sensors are installed to configure speed or torque control of the motor. Static axial load or WOB is applied to the bit with the help of two pneumatic cylinders. Hydraulic systems also work in parallel with the pneumatic system to add high frequency content of the axial load at the bit. It can generate an axial load up to 500 kgf at 100Hz [96]. Drill cell is designed to contain rock sample and bit during the experiment which can also simulate the effect of drilling fluid rheology, downhole pressure, and flow rate. Mud circulation system is composed of a positive displacement pump which helps to flow drill mud through the drill string to beneath the bit and the flow rate can be rang up to 200 liter/min.

For LDS, cutting collection system can be designed based on flow rate and operating pressure. LDS can operate in both high pressure with high flow rate and in atmospheric pressure and with low flow rate.

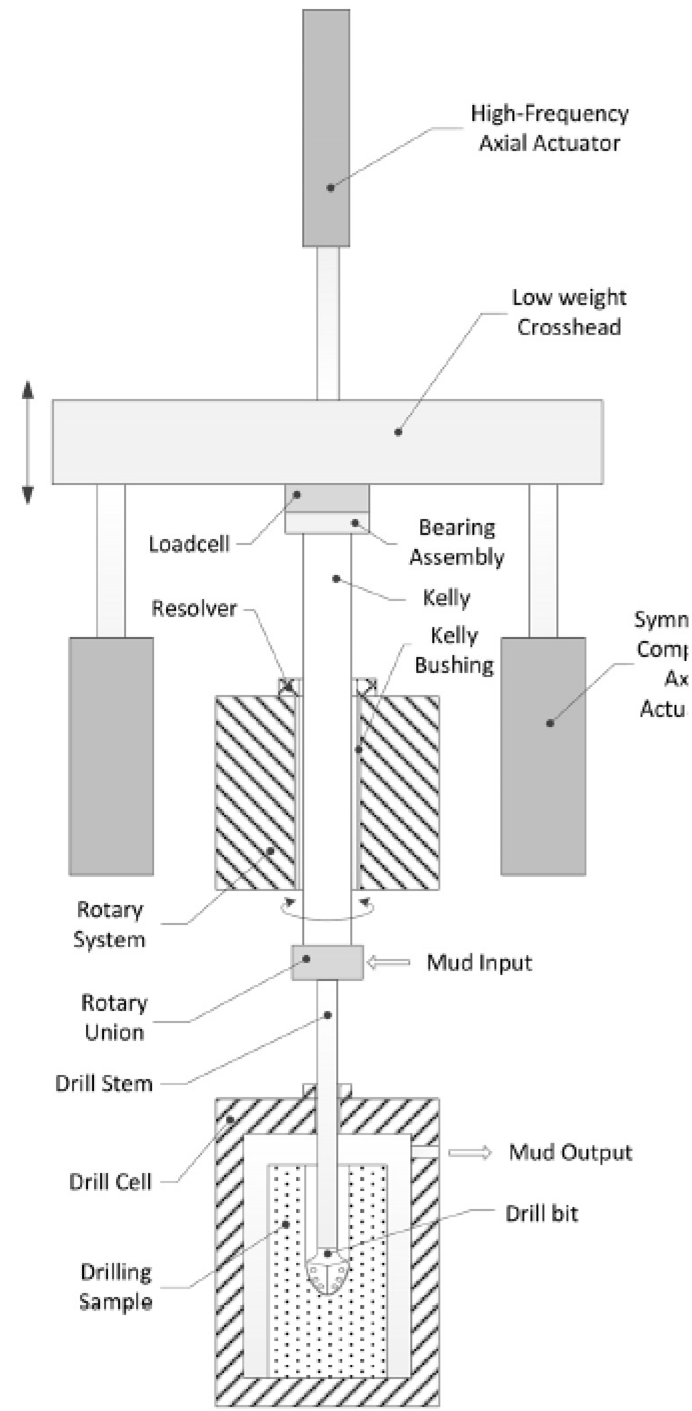


Figure 53: Simplified schematic of Large Drilling Simulator (LDS) [96]

For design criteria, a flow rate of 40 liter/min from tap water line and a 200 liter/min from triplex pump are considered for atmospheric pressure and high-pressure condition accordingly. The same configuration of a cutting collection system as the SDS is installed with the LDS. Figure 54 below illustrates the installed cutting collection system with LDS.

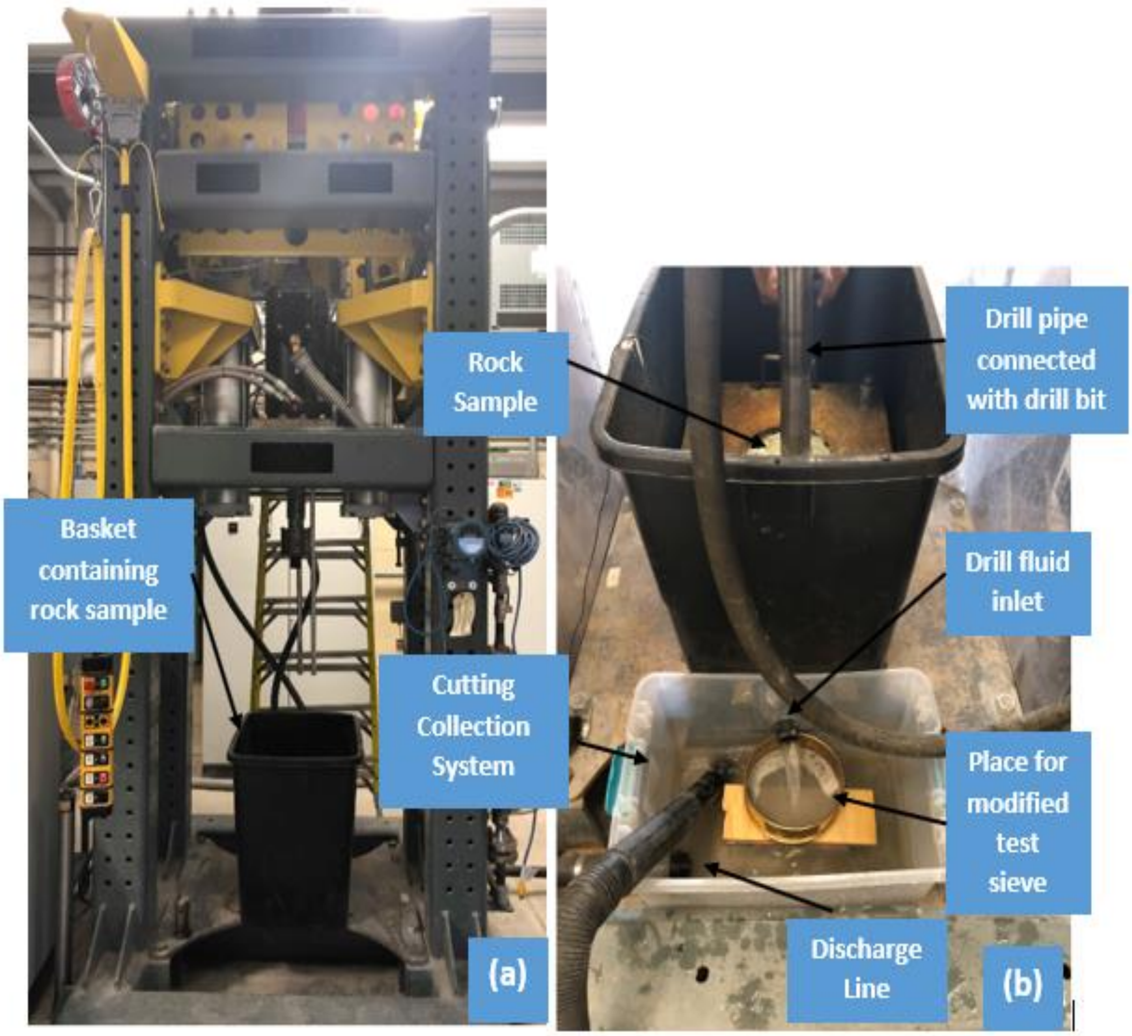


Figure 54: (a) Front view of LDS and (b) cutting collection system installed in back side of the LDS for 40 liter/min flow rate and atmospheric pressure

When incorporating a higher flow rate and a high pressure in drilling experiments, a mobile cutting collection system is designed with the similar concept of a solid control system from the petroleum industry. This system is composed of a modified test sieve of 15-inch diameter and 20-inch height placed in a water tank of 20 in length X 20-inch width X 40 inch height dimension that can bear a 200 liter/min flow rate (see fig 55 - 56). Figure 57 demonstrate the overall placement and installation system of the cutting collection system for the LDS.

Figure 55: The design of the modified sieve with dimensions

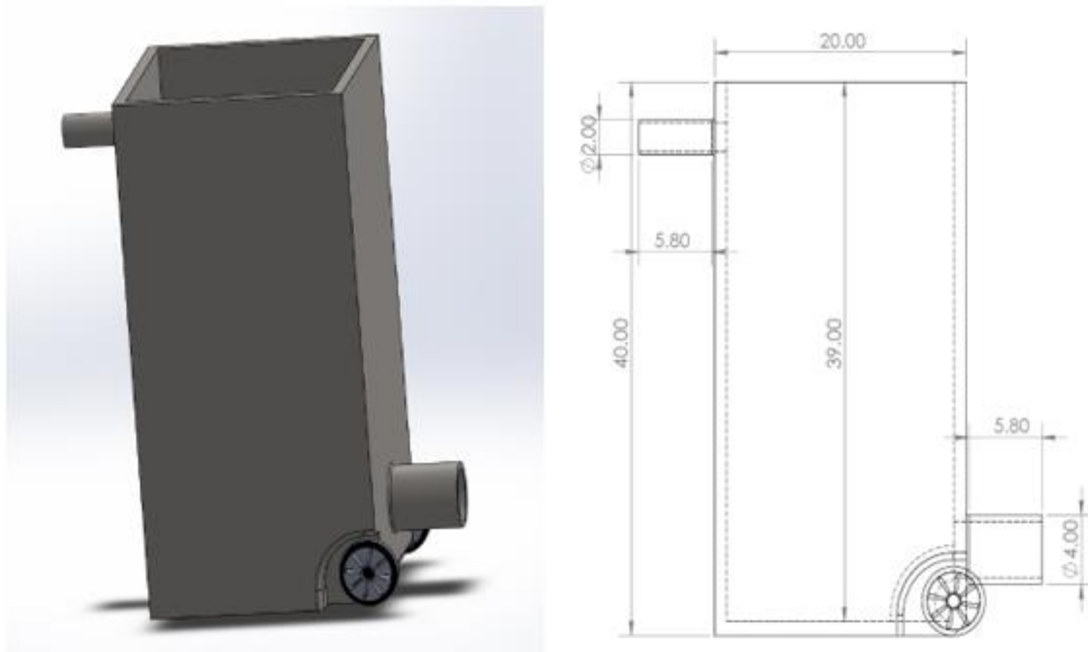


Figure 56: Design with dimensions of the big water tank

The dimension of the modified sieve is selected based on the experimental data where the flow rate was measured through the available 75-micron sieve. Based upon the experiment data below the flow rate is calculated for different sieve sizes. Table 6 below shows the calculated flow rate for different dimensions of the sieve.

Table 6 Flow rate calculation with different sieve dimensions

Dimension	Surface Area	Flow rate (Approx.)
Diameter = 12 in Height = 0 in	Area = 113 in^2	23 L/min
Diameter = 14 in Height = 10 in	Area = 594 in^2	121 L/min
Diameter = 09 in Height = 11 in	Area = 374 in^2	76 L/min
Diameter = 20 in Height = 15 in	Area = 1257 in^2	255 L/min
Diameter = 15in Height = 20 in	Area = 1120 in^2	227 L/min
Diameter = 17 in Height = 20 in	Area = 1295 in^2	263 L/min

From the analysis it is found that to attain the flow rate of 200 L/min that is generated by the pump in the laboratory, a sieve can be made of a diameter of 15 inch with height of 20 inch. The water tank needed to be installed with the LDS to carry the water from the discharge line.

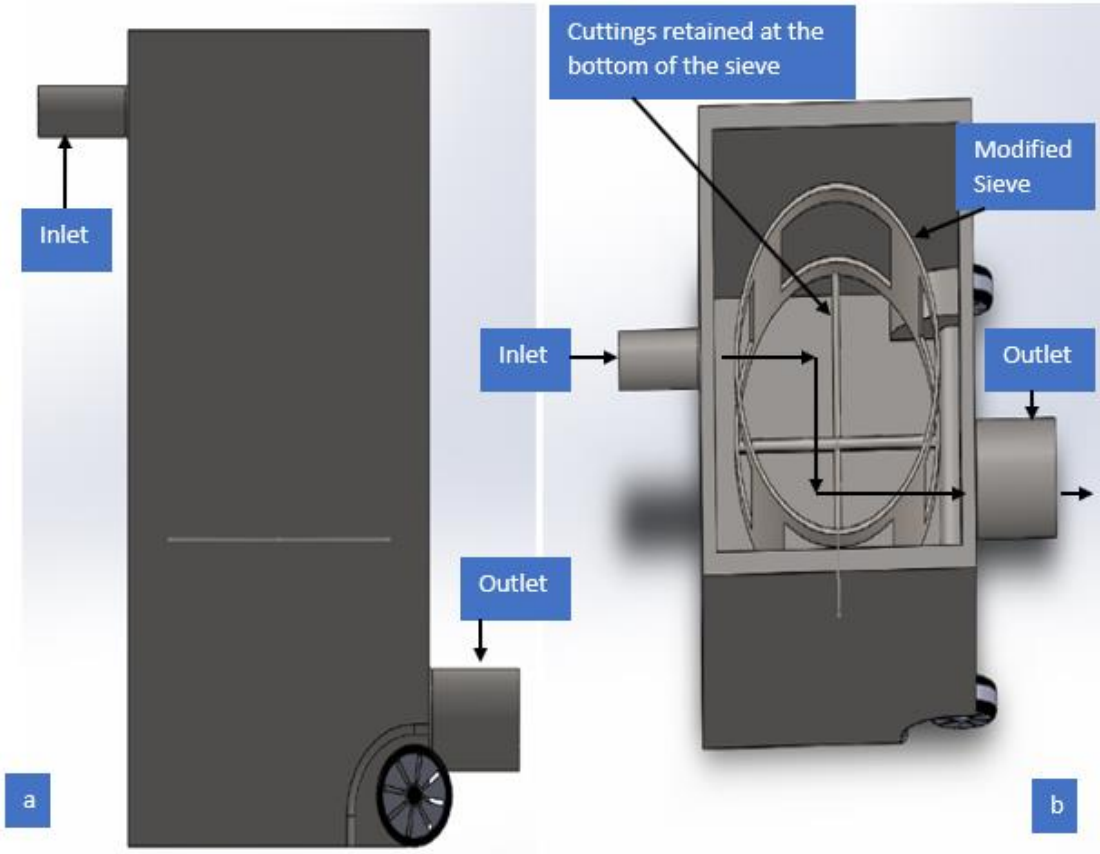


Figure 57: (a) Side view of the cutting collection system and (b) Top view of the cutting collection system

From the above-mentioned dimensions of the water tank the capacity of the tank is (40-inch X 20-inch X 20-inch = 16000 cubic inch), which is equivalent to 263 liters. This tank capacity is bigger than the flow volume per minute and it can hold the water without any flaw.

5.5 Experimental data analysis for mesh size selection

In general, meshes are used in test sieving to perform particle size distribution and in mud circulation systems meshes or screens are used to retain the larger particles from the mud. These screens work as a ‘go no-go’ indicator where particles larger than the mesh size remain in the screen for abandonment. For any screening, the design criteria involve following characteristics of the screen for better performance, such as retaining undesirable particle sizes, large fluid flow rate capacities, longer life spans, and economic viability [97]. For this design purpose, several criterions like fluid flow of 200 L/min form the pump, fluid flow of 490 L/min from the tap line, availability of the manufacturing materials, cost of material and the cost of manufacturing the system were evaluated. Mesh or screen was selected based on the analysis of several experimental data where two types of hard rock were drilled using SDS and LDS for both pilot hole and hole widening drilling operation.

The size of the openings in the screen determines that the separation can be performed by the screen. To generate uniform square apertures wire-cloth screen are woven. These screens can be plain woven or twilled woven.

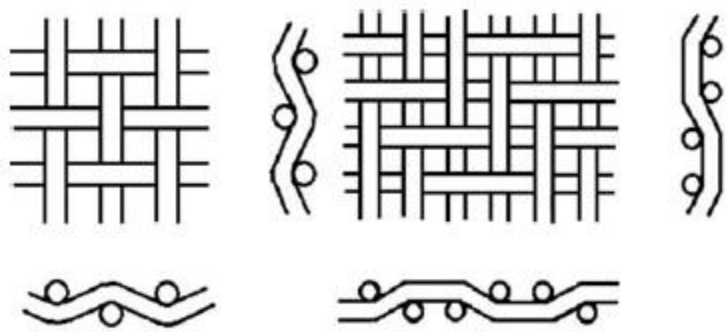


Figure 58:   Example of plain woven and twilled woven wire clothes

Screens that have an aperture greater than 75 microns are plain woven and those with an aperture less than 63 microns are twilled woven. The screens with an aperture larger than 1 mm are made up of a perforated plate sieves with round or square holes. In industry, the standard size of mesh less than 20 microns are not available for use. To identify the sieves, woven wire sieves are designated by a mesh number which is the number of wires per inch [55].

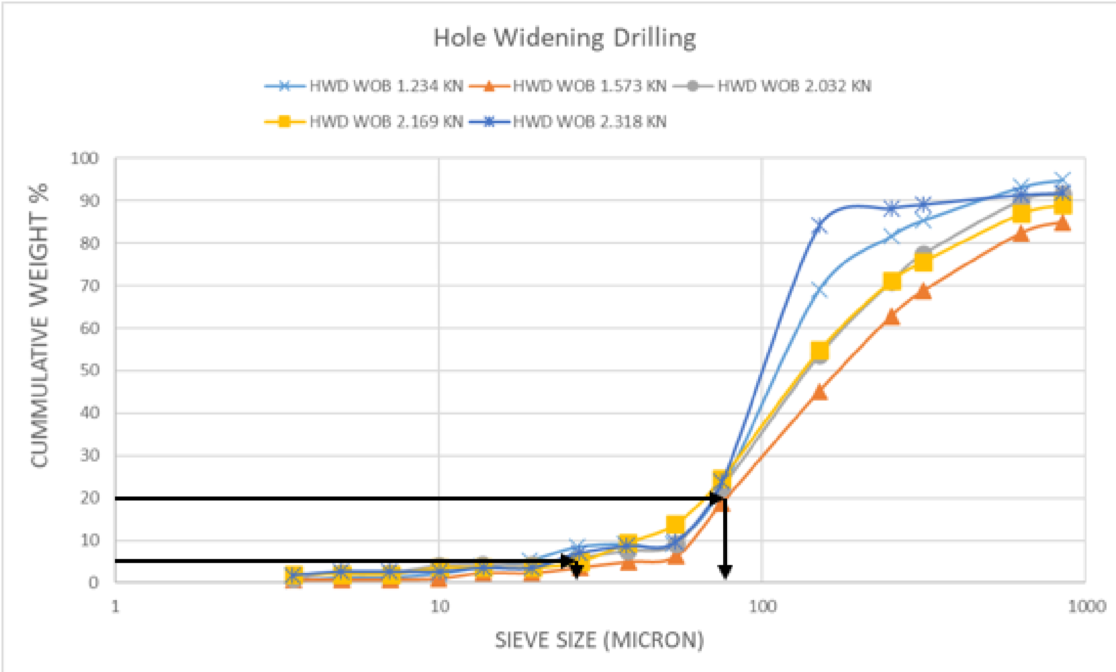
Table 7:   Showing the relationship between the mesh number and the aperture size in microns

Mesh Number	**Nominal Aperture size (microns)**
18	850
30	500
60	250
100	150

200	75
400	38
635	20

Different Drill-Off Tests were conducted using SDS and LDS in the Drilling Technology Laboratory. Based on the particle size distribution data aperture size of the screen was selected. An experiment was conducted on a hard rock sample using SDS to evaluate hole widening drilling. The details of the experiment are included in the chapter 4. In that experiment, cuttings generated by drilling operations were collected using a cutting collection system. The researchers tried to collect all the cuttings with drilling fluid and separated the fluid from the particles by using a gravity separations system.

After the collection, cuttings were studied for particle size distribution, and PSD diagrams were created along with the retained volume calculation. For particle size distribution, cuttings were analyzed using test sieving methods and hydrometer analysis. From the PSD diagrams it was noticed that for most of the trials for hole widening operations, 80% of the particles are bigger than 63 microns and only 5% of the particles are smaller than 20 microns. For pilot hole drilling, particle size was smaller than the hole widening operation and 10% of the particles were less than the size of 20 microns. Figure 59 shows the PSD diagrams for hole widening drilling and pilot hole drilling operations.



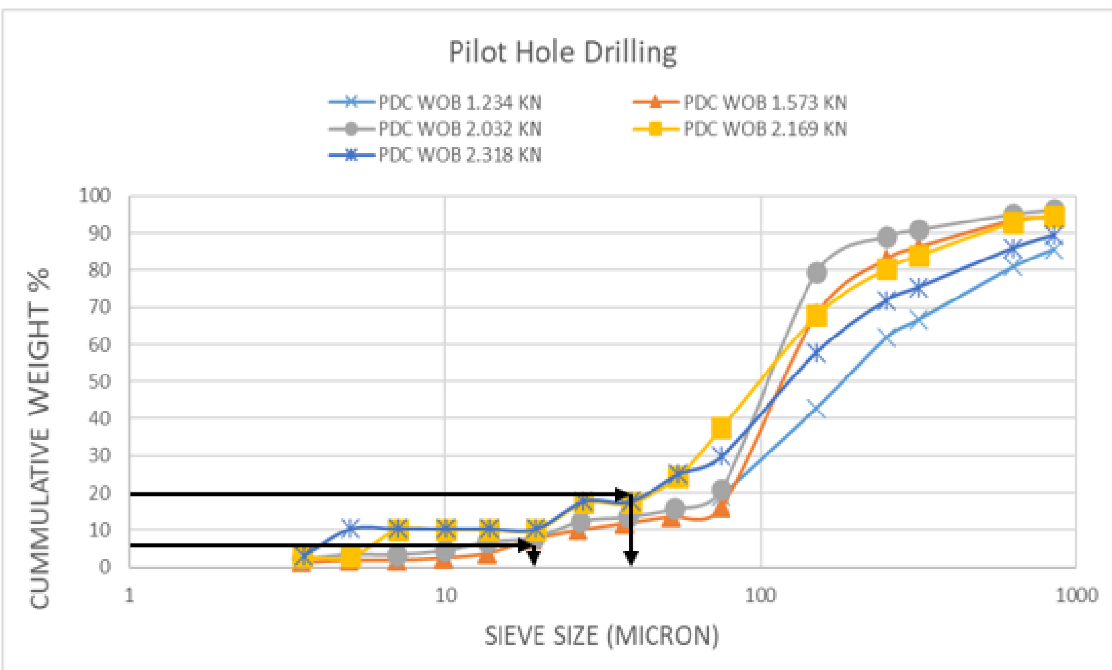


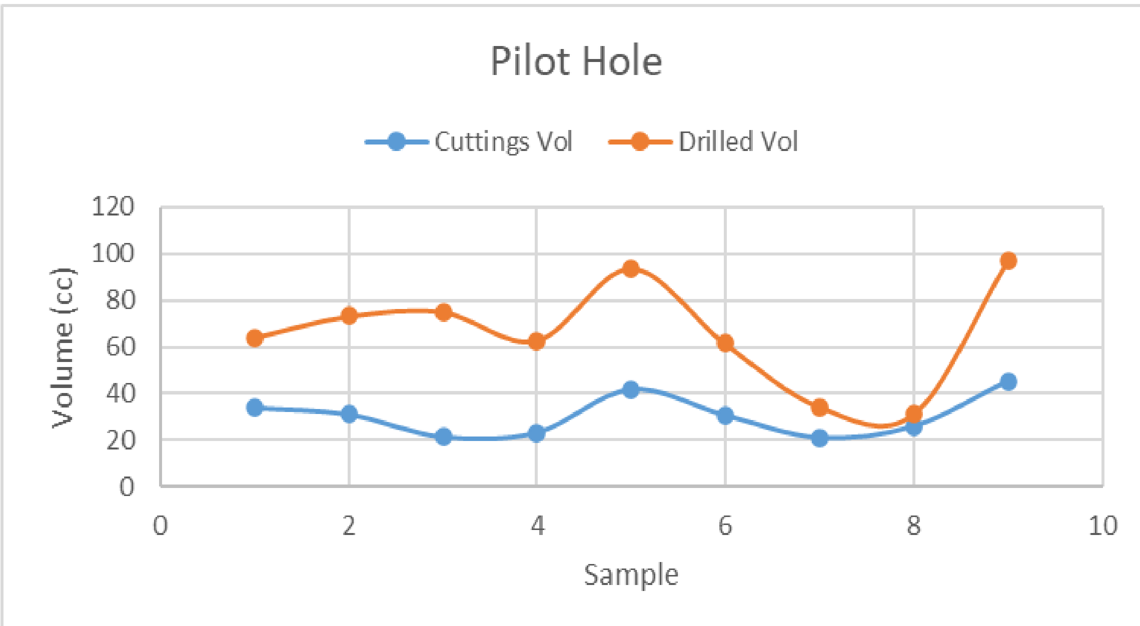
Figure 59: Particle Size Distribution for hole widening drilling and pilot hole drilling operations

Experiments were conducted using LDS on hard rock for analysis of the hole widening operation. In these trials, a pilot hole was drilled with a 63.5 mm diameter roller-cone bit and then a hole opener was used to perform a hole opening drilling of 114.3 mm diameter on the same hole. For each run cuttings were collected using the cutting collection system described earlier where a screen of 75 microns was used as per the availability in the lab. As mesh was 75 microns in size it could only retain cuttings larger than 75 microns. To evaluate the usefulness of the mesh of 75-micron, volume of the cuttings generated in each run was calculated and volume retained in the sieve was calculated for comparison. The following table shows the volume calculation analysis for these experiments.

Table 8: Data showing the comparison between collected cuttings and generated cuttings during drilling

	Sample	Measured Weight (gm)	Density (g/cc)	Cuttings Vol (CC)	Depth Drill (cm)	Area of Bit (cm2)	Weight (gm)	Drilled Vol (CC)
Pilot Hole	1	87.6	2.59	33.82	2.02	31.66	165.68	63.977
	2	80.3	2.59	31.00	2.31	31.66	189.47	73.15
	3	55.3	2.59	21.35	2.37	31.66	194.39	75.052
	4	60.2	2.59	23.243	1.98	31.66	162.40	62.70
	5	108.1	2.59	41.73	2.96	31.66	242.78	93.74
	6	79.5	2.59	30.69	1.94	31.66	159.12	61.433
	7	54.7	2.59	21.11	1.08	31.66	88.58	34.20
	8	67.3	2.59	25.98	0.98	31.66	80.38	31.03
	9	117.4	2.59	45.32	3.06	31.66	250.99	96.90
Hole opening	10	178	2.59	68.72	1.49	70.94	273.76	105.70
	11	144	2.59	55.59	0.9	70.94	165.36	63.84
	12	149.6	2.59	57.76	0.85	70.94	156.17	60.29
	13	297.2	2.59	114.74	2.35	70.94	431.7	166.79
	14	179.6	2.59	69.34	1.67	70.94	306.83	118.46
	15	174.3	2.59	67.29	1.08	70.94	198.43	76.61
	16	230	2.59	88.80	1.44	70.94	264.57	102.15

From analysis it was observed that with a 75 microns mesh size, from the pilot hole drilling experiments 50% of the total cuttings were retained whereas for the hole widening drilling it could retain approximately 80% of the particles that pertains only 20% of the total particles were smaller than 75 microns . Figure 60 below illustrates the graphs for comparing the volume of cuttings to the volume retained.



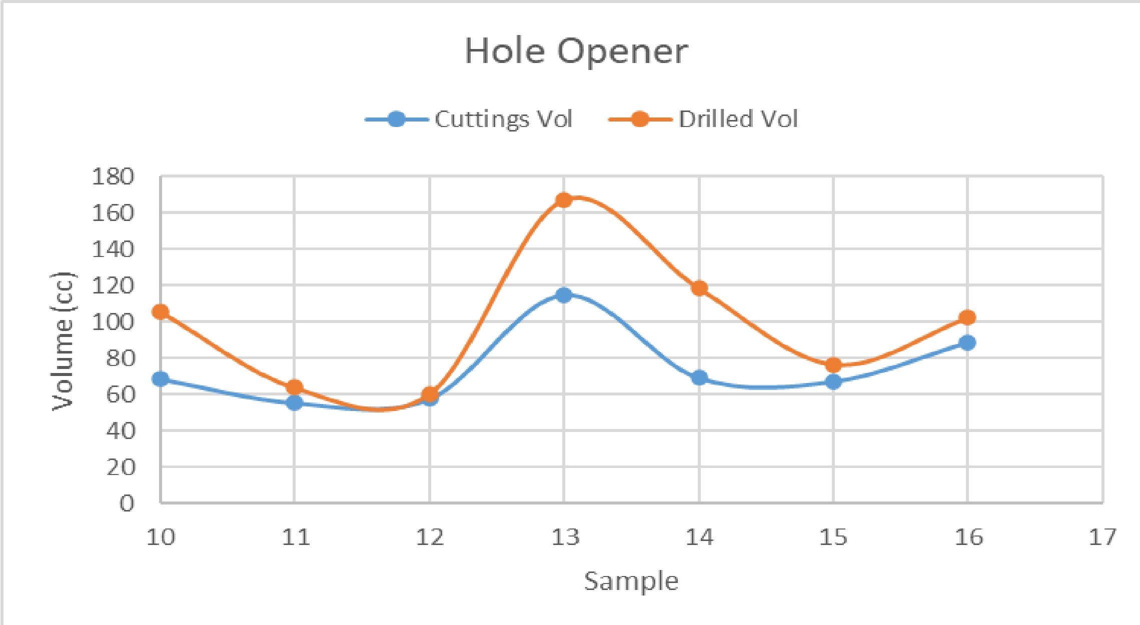


Figure 60: Illustrating graphs that show the comparison between retained volume and generated cuttings volume for both the pilot hole and hole widening operations

From the above analysis it was observed that for proper cutting collection in both SDS and LDS, the mesh or screen of 20 micron can be utilized which can retain about 90% of the total drill cuttings generated during experiments for both pilot hole and hole widening operations.

5.6 Discussion

The cutting collection system developed for the Drilling Technology Laboratory (DTL) was designed on the basis of experimental data and similarity with the cuttings separation system used in the fields. The specifications of the system are determined by analyzing the flow rate of the circulation system, the flow rate through the mesh, the capacity of the water tank used in the outlet, the capacity of the modified sieve to retain the cuttings, and the volume of the cuttings generated in different trials. The materials used in the manufacturing of the system was selected based upon the availability in the market and economic sustainability. Some modifications may possibly be needed in the future as this system is designed by keeping in mind the current specifications. Changing specifications can cause moderate change to the system design such as height of the water tank, the discharge line diameter from the tank, or the placement of the modified sieve in the water tank.

Chapter 06: Summary and Conclusion

6.1 Summary of the Present Work

This chapter summarizes the thesis work with concluding remarks and recommendations for future work that contributes to the broader field of large diameter hole drilling process. In the tenure of this research work, a hole widening drilling process was evaluated and compared with conventional pilot hole drilling through particle size analysis. Relations have been found between different large hole drilling parameters and the drill cuttings particle size by performing an extensive literature review and lab-based experiments.

To study the large diameter drilling process, an extensive literature review was performed on the history of large diameter drilling, the hole widening drilling process, the tools used in large diameter drilling, and the results obtained from different large hole drilling projects from around the world.

As the drill cuttings operate as a valuable source of information for the drilling process and subsurface geology, it is essential to collect all the cuttings while running any type of drilling experiment. From this point of view, a detailed design of a suitable cutting collection system for the DTL lab was produced and presented in the thesis, based on the physical drilling simulator setup, the flow rate of the drilling fluid, the layout of discharge lines and the volume of fluid accumulation.

6.2 Research Contribution

In this study, the main objectives were fulfilled by achieving the results for hole widening drilling in a similar manner described by the researchers in the scope of conventional rotary drilling. The following remarks are the contributions of this current research provides for the field of hole widening drilling and particle size analysis.

- For large diameter hole drilling, the hole can be drilled in a single pass method to discover the geology of the formation or the geometry of the ore body to be unearthed.
- Researchers have been working on modifications and improvements of drilling fluid additives to generate better drilling performance and borehole quality in the oil and gas industry.
- The performance of a hole widening drilling process can be assessed by thorough analysis of the drill cuttings particle size.
- Different percentile values can be read off the Particle Size Distribution (PSD) diagram or can also be calculated mathematically using a formula to characterize the particle size distribution in an intensive manner.
- The Coarseness Index (CI) and the mean particle size (d) are the two most important factors to provide a better quantitative assessment of the PSD. For large hole drilling, investigators have established a close relationship between specific energy (SE) and CI from results of several projects and laboratory experiments. Mean

particle size diameter has a demonstrated influence on drilling performance and efficiency.

- Compared to the pilot hole drilling, a hole widening drilling generates coarser particles with the same drilling input parameters and setup. Hole widening drilling produces higher ROP and lesser RPM than conventional rotary drilling.
- Energetically hole widening drilling is less costly than pilot hole drilling as MSE for hole widening drilling results in a smaller value. Higher ROP and lower MSE ensued from hole widening drilling make this process more efficient than other standard drilling processes.
- From the experimental results, it is evident that optimum WOB is a crucial factor to produce better efficiency for a drilling operation. A higher than optimum WOB, results in regrinding or crushing of the particles beneath the bit thereby, increasing energy consumption. Structural geology of the formation, internal fractures, joints, bedding, rock mass quality, strength of rock and abrasiveness also effect the performance of a large diameter drilling process.
- Better accuracy in hole cleaning and in the volume of cuttings collected effect the particle size analysis to assess drilling performance accurately. The designed cutting collection system will provide better solution and will mitigate the earlier problems regarding cutting collection from any type of lab-based drilling experiments in the Drilling Technology Laboratory (DTL).

6.3 Limitation of the work

The Mechanical Specific Energy (MSE) calculated to evaluate drilling efficiency for hole widening drilling did not incorporate parameters related to bit hydraulics. Only mechanical parameters were used in the calculation of the MSE which is one of the limitations encountered in the research.

Pilot hole drilling and hole widening drilling were conducted separately on a single hole for analysis in this research, whereas continuous drilling of a pilot hole with hole widening is performed in the industry.

Design of the cutting collection system and validation of the design depends on the results from the drilling experiments performed with current specifications of the simulators and current setup of the simulators.

6.4 Industry Application

Large diameter drilling processes have gained immense attention for the excavation of the narrow ore bodies. Mining by Drilling technology has evolved as an innovative solution for extraction of steeply dipping narrow veins.

Analysis of the particle size and evaluation of the drilling performance of hole widening has a significant industry importance as drilled particles can be retained from the drilling fluid as valuable minerals. The particle size distribution of the cuttings generated while excavating has a direct relationship with the drilling or cutting efficiency and an experienced field engineer can control the efficiency of the large hole drilling process by observing the chip or particle size [67]. With optimum drilling performance and particle size, the mining by drilling technique will result in lower investment and greater profit which is the main goal for any industry.

6.5 Recommendation for future work

Further study in the following areas can be considered for future development:

- In the field, large diameter drilling is performed using several types of cutters. Such cutters can be used to perform lab-based drilling experiments with higher WOB. The Large Drilling Simulator (LDS) can be used for the experiments and can provide higher WOB with varying rotary speed.
- Extensive analysis can be performed to create a new model or to validate already established models for the estimation of the particle size using drilling parameters.
- Particle size analysis recommends using sieve analysis along with sub-sieve techniques to learn about the smaller range of particle size. Dimensions of the bigger particles are very important for investigating performance. It is also recommended to measure the dimensions of the bigger particles generated from the large diameter drilling experiments.
- A simulation study is suggested for future work to compare and validate the experimental data with the simulation data for large diameter drilling.

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