CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, basic technical knowledge and recent research development related to the area of research topic, are discussed to develop a thorough understanding. These basics are also helpful during laboratory experimentation and interpretation of results obtained.

2.2 Rock Drilling

The process of making holes through the rock strata of predefined parameters (diameter, depth, and direction) for any desired purpose is known as rock drilling. The process involves breaking and shearing forces on the rock surface. These forces are applied through a rock cutting tool known as a drilling bit. The efficiency of drilling operations can be decided on the basis of the cost, safety, and rate of progress in the rock to achieve the desired purpose. On the basis of the mechanical rock breaking principle, rock drilling can be broadly divided into two types, namely Rotary drilling, and percussive drilling. The forces applied on the bit-rock interface during a rotary drill process include both axial and rotational forces.

2.3 Purpose of Rock Drilling

Rock drilling has a very significant contribution to industrial evolution. There are many purposes of rock penetration for the industries aiming toward the excavation of natural resources (mineral, gas, and petroleum) and many others. Some of the important purposes are:

1. To understand sub-surface geological conditions by drill hole inspection like lithology, bedding plane, and discontinuities, etc.

2. To get the rock samples for laboratory studies of geotechnical parameters like porosity, permeability, and strength. Also for in-situ tests of rock strata.
3. To explore the existence of mineral deposits and delineate their extension.
4. To drill production holes for charging explosives in semi-mechanized and mechanized mine workings.
5. To drain out harmful gases (such as methane drainage) and accumulated water from old and abandoned mine workings.
6. To lay stowing pipes, water pipes, electrical cables, signal wires to below ground from surface.
7. To freeze the ground to mine out the highly saturated and fractured strata by injecting liquid nitrogen in a ring of holes around the area to be mined (for example, shaft sinking).
8. To provide better ventilation to underground mine workings through boreholes.
9. To deploy various rock supports like rock bolting, and roof stitching, to prevent the sliding of loosened rocks by strengthening them in-situ, this can be called blind reinforcement.
10. To continuously maintain the mine water level, pumping holes are placed surrounding the mine to provide dry working condition.
11. To observe the condition of water logging ahead of underground working face and also for dewatering through Burnside boring apparatus.
12. To extract the block of dimensional stone precise drilling is required.

Rock drilling technology is also a very useful aspect of the civil engineering and construction industries. Some important constructional works are tunnel boring, water boring, a gas reservoir, laying the foundation for dams, bridges, and tall buildings, support to sidewalls, and hanging rocks in hilly transportation ways by rock bolting in hanging wall. For adequate foundation design for large engineering structures, study of subsurface strata is one of the deciding parameter. Soil sampling and subsurface study for various purposes are some of the major use of drilling and coring technology in soil engineering field.

Nowadays continuous inspection of any historical and important structure is very necessary to take timely precaution. This is to protect the structure, human life, and wastage of money. For the aforesaid purpose, coring is to be done for a sample collection from different load-bearing portions. These samples are collected for laboratory testing to check the condition of structures like dams, tunnels, roads, and other structures of importance, etc. at regular time intervals. Also for continuous inspection, installing real time measuring instrument in the hole drilled on load bearing portion of structure, is one of the important process.

2.4 Importance of Drilling in Mining

Drilling has amply impacted the individual process of the mining cycle, i.e. drilling, blasting, hauling, crushing, etc. For example, explosives consumption, fragmentation size, and distribution of fly rock, controlled blasting, need for secondary blasting, and toe formation at the bench, etc. depend on the accuracy of the drilling operation.

Over-size boulders generated due to inaccurate drilling bear a direct impact on the productivity of hauling operation and mineral dressing cost. In the case of dimensional stone mining, the quality of drilling operation is very important, where the intactness of block and micro-cracks are important areas of concern. The drilling process alone costs 19.04% of the overall mining cost per tonne of ore production. [Gary 2016]

2.5 Drillability

Rock drillability can be defined as ‘Penetration rate of a drill bit into the rock’, or ‘Resistance to penetration of rock’ is called as drilling strength and some researchers express drillability of rock by this parameter [Pathak 2010]. The term ‘Drilling rate index (DRI)’ is a measure of rock hardness, and is also considered as ease of rock drillability [Yenice et al. 2018].

Drillability depends on the combined effect of in-situ properties of rock and operational parameter of drilling. In-situ properties are the physico-mechanical and geological properties of rock. Operational parameters includes, inter-alia, type of drill machine, bit geometry, thrust, torque, bit rotational speed, and type of flushing media, etc. [Beste 2007]

These factors could be broadly characterized in three groups, namely:

(i) Controllable parameters;

(ii) Uncontrollable parameters; and

(iii) Skill & experience of the drill operator, and health of the machine.

2.5.1 Controllable Parameters

Machine parameters are considered as controllable parameters. Some of the salient parameters are:

2.5.1.1 Bit Type and Geometry

Drill bit type, diameter, geometry, and material used in the manufacturing of it, have a significant impact on the rate of penetration rate. The large diameter drill bits are more capable of withstanding various forces produced during rock penetration, such as longitudinal, radial, tangential, shock and vibration, etc. The limit of maximum applicable thrust can be increased by increasing bit diameter [Miller et al. 1990].

For best efficiency, the number of cutting teeth on the drill bit and the type of material used in the manufacturing of teeth could be selected on the basis of the type of formation to be drilled. More number of shorter teeth of high-density material is best suitable for a strong rock formation.

2.5.1.2 Load on Bit

It is also known as "thrust", which helps in (i) keeping the bit in contact with rock face for better penetration, (ii) feed the bit in a forwarding direction, and (iii) counter-weight to the rebounding force. Thrust and penetration rate are directly proportional up to a limit, depending on rock type and drilling machine. But after that limit, excessive thrust may cause torque increment and an increase in bit wear. [Bhatnagar et al. 2010,2011]

2.5.1.3 Rotational Speed of Bit

In rotary drilling, the prime mover (motor) provides the rotational force to the bit. It can be expressed in terms of rotation per minute (RPM). The penetration rate is directly proportional to the rotational speed of the cutting tool. The effect of RPM on penetration rate can be measured by calculating the depth covered in one rotation of the cutting tool or bit. By the rotation of a bit, the rock surface begins to deform under the shearing force [Mustafa et al. 2021]. So, as the rotational speed increases, it fastens the shearing and increases the penetration rate.

2.5.1.4 Flushing Media

It is one of the crucial parameters, that affects the overall efficiency of operation, easiness, and safety. Flushing of hole helps in cleaning the rock cuttings from the hole bottom - thereby exposing new surface, cool the bit, and lubricate whole down the hole assembly, etc [Bhatnagar et al. 2011]. There are many important sub-factors, that affect drilling performance like state of fluid and its density, concentration of different additives, speed of flushing, etc.

2.5.2 Uncontrollable Parameters

In-situ rock properties are the inherent ones and hence, are not controllable. Some of the salient parameters are as follows:

2.5.2.1 Strength

As the strength of rock (compressive, tensile, and shear) increases, the rock becomes much harder to drill.

2.5.2.2 Hardness

Normally, it is accepted that the drillability of rock is directly proportional to hardness, for most of the rocks.

2.5.2.3 Abrasiveness

The abrasiveness of rock can be defined as the tendency of a drill bit to wear while contacting with a rock. This rock characteristic has the main effect on the percentage of quartz content of rock. As the percentage of quartz increases the abrasiveness of rock also increases. In general, the penetration rate decreases with an increase in the rock abrasiveness. In the case of drilling with a diamond impregnated bit, the abrasiveness of rock helps in improving penetration rate due to sharpening of the bit by exposing fresh diamond grits by abrading the matrix [Rao et al. 1998]. Shankar et al. (2020) have found that drilling the rock with high silica content, causes an increase in the frictional heat at the bit-rock interface.

2.5.2.4 Texture

The rock texture can be defined as size, shape, and orientation of the grains or crystals. The combined effect of various grain properties provides texture co-efficient of rock, namely grain size, grain circularity, grain elongation, grain orientation, and degree of grain packing. As the value of the coefficient of texture increases, the rock becomes more difficult to drill [John et al. 2021].

2.5.3 Skill & Experience of Operator and Health of Machine

In every field, skill and experience of machine operator is very important. In the case of drilling machine, if the operator has good technical skills and experience about machine and field, he may be able to serve good productivity. On the other hand, even with a very good operator and favourable working conditions, if machine health is not up to the standard, it would be difficult to achieve high efficiency and productivity. Health of machine can be measured in terms of life of machine, repairing and maintenance of machine, and user friendliness of machine etc.

2.6 Methods of Predicting Drillability

Many methods have been suggested by researchers for the prediction of drillability. These methods could also be used to define the efficiency of a drilling system. In this study, the drillability has been predicted on the basis of the following five parameters:

(i) Rate of penetration (ROP)
(ii) Specific Energy consumption (SEC)
(iii) Bit Wearing
(iv) Machine vibration
(v) Bit temperature

2.6.1 Rate of Penetration (ROP)

It is defined as the rate of advancement of the drill bit into the rock strata. In other words, ROP is a measurement of depth covered in rock strata by the bit in a unit time interval. It can be calculated as a ratio of ‘depth covered by drill string’ to ‘the time taken’ in covering that depth - so, the unit of ROP is ‘m/min’ or ‘mm/sec’. The compressive strength and abrasiveness of rock exhibit strong correlations with the penetration rate. These two are dominant properties compared to the other rock properties. They are inversely proportional to the rate of penetration (ROP) [Ngerebara et al. 2014, Hayati et al 2019, Kahramana et al. 2003, and, Kahraman et al. 2003]. Along with above mentioned properties rock hardness, textures, density, and fractures etc.also plays vital role [Singh B., and Goel 2011]. Ramsey (2019) found proportional behaviour of ROP with weight on bit, bit rotational speed, and flushing rate.

2.6.2 Specific Energy Consumption (SEC)

Specific Energy Consumption (SEC) in drilling is calculated as ’the energy required to drill unit volume of rock’. It is expressed in the unit of ‘GJ/m^3’ [Teale 1964, Messaoud 2006, Celada et al. 2012]. It can be measured by the ratio of ‘total energy consumption in drilling a hole’ to ‘total volume of rock removed from that hole’ or energy required per cubic cm (or unit volume) rock drilled [Khosravanian R., and Aadnøy 2022]. While using an electric-powered drilling machine, the SEC is expressed in the unit of ‘kWh/mm^3’. In this situation, electrical energy is converted into mechanical energy. The mechanical energy consumption in the drilling process includes mechanical losses, torque, friction, drag, and vibration.

2.6.3 Bit Wearing

It can be described as a loss of cutting element (either by wearing or by extrusion) while drilling unit depth in rock. Many researchers have recommended multiple methods to measure bit wearing and found rock abrasiveness as one of the key responsible factors. [Kenda et al. 2009, Guttenkunst 2018, Thakre et al. 2019, Shankar et al. 2020]. Miller (1991) has visually investigated the bit wear during rock drilling with the help of an optical scanning electron microscope. Thakre et al. (2019), have used image analysis of worn-out bit, for the measurement of bit wearing. Lin et al. (1992) have studied the wear pattern of polycrystalline diamond compacts bit and stated that the frictional heat and cooling due to drilling fluid may cause thermal fatigue, which leads to higher formation of a wear flat. The wearing of the polycrystalline diamond compact (PDC) drill bit has four stages in sequence namely, break at entry, wear at layer of diamond, subsequent wear at the carbide layer's substrate, and rapid break- down [Hough and Das 1985]. In this study, bit wearing was measured in the context of bit weight loss after drilling a pre-defined depth of the hole.

2.6.4 Machine Vibration

Vibration during drilling operations always being a challenge for industries. This unwanted vibration can affect the machine efficiency and operator's health too. The pivotal challenges brought on by drill string vibration include drill string component failure, bit failure, inefficient drilling, bit and stabiliser wear, low penetration rate, and decreased efficiency [Bailey et al. 2008]. The vibration acceleration (in m/s^2) can be measured with a vibration analyzing instrument, installed externally on the desired location of the machine. The root means square (RMS) and vibration total value (VTV) values can be taken into the consideration to analyze the vibration [Yafeng et al. 2021]. Kumar et al. (2020), have observed that during rotary drilling the axial vibrations were higher compare to lateral. It was also found that with the increasing ROP and thrust, the machine vibration showed a decreasing trend. A researchers group have studied the resonance drilling with PDC bit, and concluded that with an increase in the harmonic vibration frequency, the rock drillability decreases. [Wei et al. 2013]

2.6.5 Bit temperature

During drilling operation, the highest temperature in the whole drill string is attained by the bit because of the friction at the bit-rock interface. Due to this phenomenon, the bit becomes the most prone component to get worn out frequently in the drill system frequently. Increasing frictional heat can accelerate the bit wearing [Rao et al. 2002]. The pyrometer used in the experiments is a fiber-optic two-color ratio pyrometer [Muller et al. 2001, Ben et al. 2012]. Shankar et al. (2020), have installed a thermocouple transducer inside the rock sample to measure the bit temperature while drilling. It was concluded that the increasing temperature was responsible for the increase in drill bit wearing. Karstad E., and Aadnoy (1997) have observed that the temperature gradient of the rock increases with drilling rate.

2.7 Flushing Fluid

To create a hole in rock strata, drill cuttings are generated due to the forces at bit at bit-rock interface. The drill cuttings may create obstacles between the bit and the rock, if not removed from the bottom of the hole, and reduce the drilling efficiency. The process of removal of drill cuttings from the hole bottom is known as ‘flushing’.

2.7.1 Fluid Circulation System

For the circulation of drilling fluid, an additional system is required along with a drilling machine, depending on the type of fluid. A line diagram of fluid circulation is drawn in Fig. 2.1, where arrows indicates the direction of fluid flow. The pumped fluid enters from the drill string and flushes the drill cuttings at the hole bottom. The cuttings are carried to the surface with fluid through the annular space between the drill string and the hole wall. On the surface, a sieve shaker is used to separate the cuttings from the fluid. The separated fluid is passed through the various mechanical and chemical processes in the mud tank so that it can be re-used. Following indications have been observed during this experimental work:

Case 1: If the quantity of fluid is too low.

Indications:

- Reduction in penetration rate,

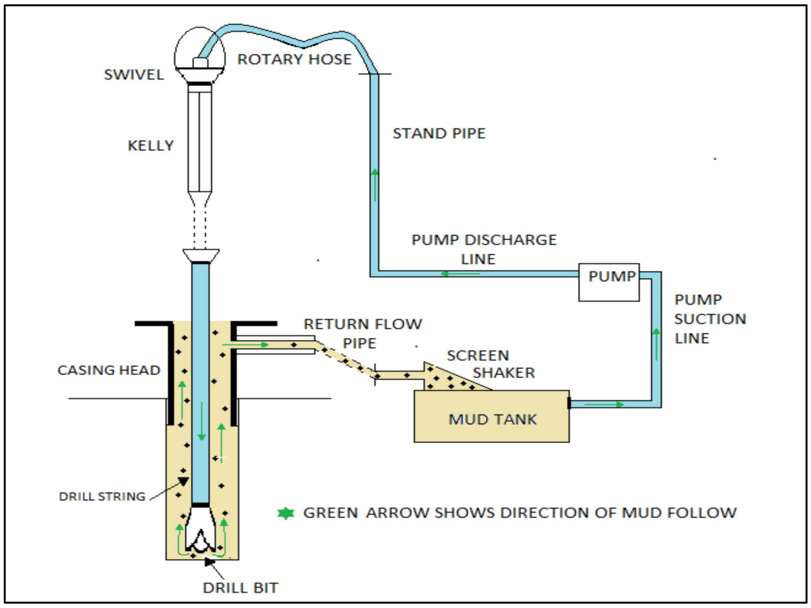

Fig. 2.1: Fluid Circulation System

- Temp. rise and polishing of rock-bit interface.

Case 2: If the quantity of fluid is too high.

Indications:

- Excessive wear on bit and matrix,
- Poor core recovery due to excessive washing of core.

These indications can be used for the optimisation of fluid flow rate. It is suggested by researchers that, in field operation, the return velocity of water-based fluid should be 30-46 cm/sec for effective removal of cuttings. It may also increase the core recovery upto 100%. It was also found that a pump pressure of 3.5 to 10.5 kg/cm^2 will be most suitable to overcome the friction created by pipe and rock surfaces in field drilling. [Chugh 1984]

2.7.2 Role of Drilling Fluid

The flushing fluid has several roles in the rock drilling operation. Some of the significant roles are:

2.7.2.1 Cleaning of drill cuttings from the Hole Bottom

The drilling fluid flows through the centre of the bit and flushes out the drill cuttings from the bit-rock interface and provides fresh rock face to the bit. It reduces the wastage of energy that takes place in the regrinding of un-flushed rock cuttings at the bottom of the hole [Larson et al. 1987, Tutluoglu et al. 1983].

2.7.2.2 Removal of the Cuttings from Hole

Proper removal of rock cuttings from the hole and carrying it up to the surface is essential. This process requires the combined action of fluid velocity and its properties like viscosity, density [Piroozian et al. 2012]. The cuttings flow through the annular hollow space between the drill rod and hole periphery.

2.7.2.3 Suspending and Settling of Cuttings

The cuttings must remain suspended in drilling fluid while it is inflow and get settled in a settling tank at the surface as fluid comes in rest. The rate of settling of the cuttings depends on the cumulative effect of the fluid and properties of the rock cuttings [Rawia et al. 2011]. By the effective completion of this purpose, the fluid can be separated from drill cuttings at the surface and re-circulated in the drilling process.

2.7.2.4 Ease of Motion

It reduces friction between the drill string and hole sidewalls, which helps in providing smooth rotation. This reduces the torque and hence the bit wear [Hirokazu et al. 2016].

2.7.2.5 Cooling of Down-The-Hole (DTH) Drill Assembly

The fluid should have sufficiently high specific heat to have an adequate coolant effect on down-the-hole assembly (i.e. drill rod, hammer, and bit). It absorbs the heat generated by friction at the DTH-rock interaction surface and within the machine parts [Harvey and Lagaly, 2013].

2.7.2.6 Lubricating of Down-The-Hole (DTH) Assembly

Drill fluid continuously lubricates the rock-DTH interaction surface and component of a machine that comes in contact with a fluid, like a drill bit, hammer and rod. In the absence of drilling fluid, bit wearing would be more frequent. It prevents corrosion and improves the life of the machine. . As per gandhi and sarkar (2016), the drilling fluid decreases vibration of drill string and hence, help in stabilising it. It can also solve many other issues like:

- Improving the hole stability,
- Improving core sample recovery of fractured rock,
- Controlling strata formation pressures,
- Preventing losses of drilling fluid losses in fractured formation,
- Protecting strata of interest from contamination by drilling fluid,
- Preventing the intrusion of formation fluid,
- Facilitating the freedom of movement of drill string and casing, and
- Filtering cake deposition.

2.7.3 Classification of Drilling Fluids

The word ‘fluid’ refers to every substance that can flow, whether it is in the form of gas, or liquid. To improve the efficiency of liquid-based drilling fluid, chemicals are added to the base fluid (like water or oil). Such chemicals are known as ‘additives’, and the mixture of base fluid and additive is known as ‘drilling fluid’. A detailed classification of drilling fluids is given in figure 2.2.

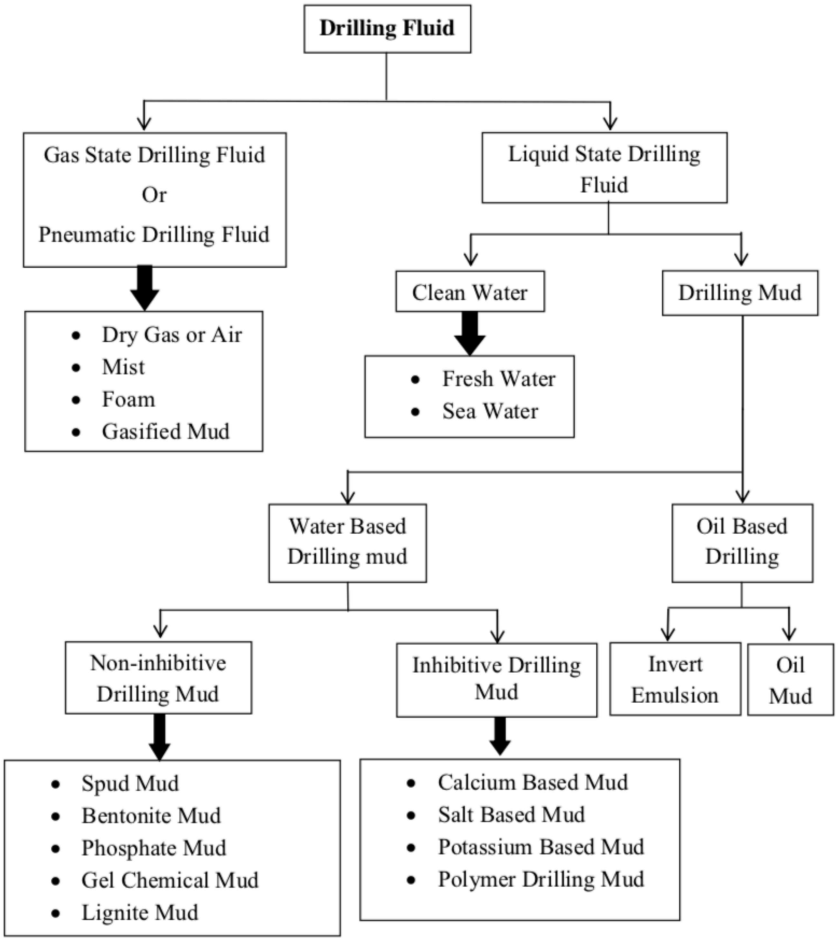

Fig. 2.2: Classification of Drilling Fluids [Azar 2007]

2.7.4 Polymer Additives

Earlier, the polymers were also known as 'Macro-molecule' or 'large molecule'. Polymer word is derived from Greek words 'Poly'(means 'many') and 'Meros' (means 'parts'). The process of making a polymer by the repetition of small units (i.e. monomer) is known as polymerization. By this process, the strength and other properties of any chemical compound can be enhanced. For example, the repeating unit of Polyethylene is $-(CH_2CH_2)^n-$, and its monomer is $CH_2=CH_2$. **[**Billmeyer et al. 1994**]**. For further improvement of the properties of the polymers, grafting of copolymers and their hydrolysis may be done.

A grafted polymer has a main linear polymer chain (called 'backbone') with multiple attachments of other polymeric side chains (called 'graft'), both are having different chemical nature. In most cases, the distribution of grafted side chains on the backbone was found randomly positioned [Paul et al. 1989]. On the other hand, in hydrolysis, a grafted polymer molecule is broken down into multiple large monomers in the presence of water. Such hydrolysed products sometimes display highly stable properties [Synthesis 2013].

Polymers are used as additives in flushing systems to achieve desired fluid properties to overcome the drilling issues. Polymers are low-solid active clay. It provides desired rheological and filtration control properties. It also improves the stability of drilling fluid in extreme working conditions, like pressure, temperature sensitivity, and contamination by strata, etc. During the drilling process use of polymer in the fluid can help in the improvement of the rate of penetration, reduction of friction and torque, improvement of machine life by continuously lubricating drill string which prevents rusting and reduce bit wearing too. Many researchers have suggested that both natural and synthetic polymers act as good additives to drilling fluid while drilling with diamond core bit [Rawal et al. 2016, Bhatnagar et al 2010, Rao et al. 2002].

2.7.5 Selection of Drilling Fluid

The selection of the most suitable and efficient drilling fluid is very crucial and some of the factors responsible are discussed below:

2.7.5.1 Overall Cost

The implementation of drilling fluid in operation involve additional cost. So, cost of additives, preparation of drilling fluid, pumping, fluid treatment, recirculation, disposal, and additional machinery setup for aforesaid works have a great influence on fluid selection.

2.7.5.2 Purpose of Drilling

Rock formations with abnormal temperature, pressure, highly sensitive rock (i.e. shale), geological discontinuities, and unfavorable working conditions pose problems during and after drilling a hole. Selected drilling fluid should be capable of solving such problems to improve the drilling performance.

2.7.5.3 Safety

Fluid should not have any toxic reactions on workers' health and wearing effect on drill machine.

2.7.5.3 Environmental Effect

Disposal of waste drilling fluid may have adverse impacts on the surrounding environment like land degradation, disturbance in flora and fauna, groundwater contamination, etc. Such effects should be minimum. Also, the fluid and additive should have easy storage, and stay inert with environmental factors.

2.8 Previous Research Review

The previous research works in related area have been review and discussed area wise.

2.8.1 Related to laboratory drilling

Carrying out experimentation on real-life rock drilling directly in the mines is not only an arduous task, but it is also uneconomical in terms of money, time and manpower. Also, the repeatability and accuracy of such experimentations are very difficult. Field experiments not only hamper the daily production of the mine but could potentially lead to dangerous situations. A small-scale drilling testing setup provides good solutions to allow engineers and developers to test innovative solutions in a safe and controlled environment [khadisov et al, 2020].

Considerable literature and field studies have provided inspiration about the need for a downscale and user-friendly laboratory rock drilling set up for experimentation. Available literature [Miller et. al. 1990, Rao et al. 2002, Bhatnagar et al. 2010] gave the necessary initial impetus for designing a laboratory-scale drilling setup.

For understanding torsional vibration, a drill string system was created by Patil and Teodoriu (2013). A small-scale rig named ASPEN was used for understanding torsional vibration while drilling rock samples using drag bits [Kovalyshen et al. 2014]. A silent laboratory drilling setup was fabricated by Masood (2015), for the estimation of physicomechanical properties of igneous rock samples using sound level produced during the drilling operation. Cayres et al. (2015) examined the effect of dry friction-induced torsional vibrations on a slender drill pipe.

To mitigate dysfunctions in downhole, an automated drilling rig was built by Bilgesu et al. (2017). Laboratory experimentation on vibration in drill setup was successfully tested by Lin et al. (2018). Real et al. (2018) have fabricated a setup to simulate the drilling process. The effect of rotary speed and weight on bit on lateral vibrations - in a highly deviated oil well - was investigated by Wen et al. (2018). The effect of the length of the drill rod on the experimental outcome was studied by Tang and Zhu (2019). Lakshminarayana et al. (2019) have used laboratory scale drilling setup and mathematical modeling to estimate the uniaxial compressive strength and Brazilian tensile strength of sedimentary rocks using the values of operating parameters obtained from the rotary drilling.

Experimental test rigs allow the measurement of mechanical parameters and a closer insight into the complex mechanisms of drill string dynamics (Westermann et al., 2015). The economic aspect and the need for repeatability in testing make the down-scaled laboratory setup the most viable option for analyzing drill machine vibrations under a wide range of variations in operating parameters (Srivastava et al., 2019).

It is an ideal procedure for experimenting with new technologies by testing them in the laboratory prior to field implementation. This gives the opportunity to carry out experimentation under controlled parameters with repeatability. After optimization of the parameters, a pilot-scale experiment can be designed for the initial validity of the results in the field. On success, full-scale field experiments can be planned.

Rock drillability is defined as “the penetration rate of a drill bit into the rock” (Yarali et. al. 2011, Prasad et. al. 2016). It depends on the combined effect of rock as well as machine parameters. Rock parameters are naturally existing ones and, hence, uncontrollable; namely strength, hardness, abrasiveness, and texture of rock. On the other hand, machine parameters are man designed ones and, hence, controllable; namely bit rotational speed, weight on bit, type of flushing medium and its rate, rock sample size, bit type, bit size, etc. (Beste et al. 2010, Servet et. al. 2014).

These experiments in field drilling setup provide conclusive insights into the complications associated with it. It justifies the need for research on the design and development of a full-scale laboratory drilling set up to study the individual effect of various parameters of rotary drilling machine (i.e. thrust, bit rotation speed, flushing parameters, drill bit parameters, energy consumption, etc.) with a wide range of rock types on the overall performance of drilling machine.

The setup fabricated in this experiment was aimed to fulfill the need for research. Also, it should allow the measurement of the rate of penetration (ROP), flushing rate, power utilization, specific energy consumption (SEC), machine vibration, and bit temperature, etc. Several research groups have worked on a down-scale system of laboratory rock drilling experimental setup, including Foster et. al. (2010), Esmaeili et al (2012), Patil and Teodoriu (2013), Patil (2013), Kovalyshen

(2014), Kapitaniak et. al. (2015), Marquez et. al. (2017), Bilgesu et al. (2017), Arnø et al. (2018), Lin et. al. (2018) and Løken et al. (2018, 2019).

2.8.2 Related to Machine Parameters

The impacts of flushing fluid on drilling performance have been a very popular issue among researchers [Berg et al. 2015, Bhatnagar et al. 2010, Bhatnagar et al. 2011, Dong et al. 2020, Echt et al. 2020, Lashari et al. 2019, Mansell et al. 2018, Paiaman et al. 2009, Rao et al. 2002]. Berg et al. (2015), had used a venturi flume to provide a cost-effective measurement of the flow rate. Huang et al. (2020) had used a novel hydrate drilling experimental apparatus to study the drilling process in the hydrate-bearing sediments to identify the influence of drilling fluid circulation rate on hydrate dissociation. Liu et al. (2015) found that a water jet's role in drilling was very beneficial. It had reduced the bit wearing, increased the rate of drilling, and enhanced the efficiency of operation. Kovscek et al. (1988) had concluded that the water pressure and the thrust positively impacted drilling rates.

The mechanism of de-lamination of rocks while drilling with water jet piercing was described with the help of the analytical approach by Cheng et al. (1990). Roderick et al. (2004), had performed the blast hole drilling with a water jet as flushing fluid and concluded that water jet helped in reducing bit wear, hole deviation, and increased the rate of penetration (ROP). In comparison to the conventional rotary drilling, here the improvement in ROP was 40%. The PDC bit forces required to drill the rock had been reduced by about 30% to 52% due to the application of water as a drilling fluid [Lu et al. 2008, Lu et al. 2010].

Power consumption in rock drilling has a direct impact on its performance. A high rate of penetration (ROP) with optimum power consumption dictates the economic performance of drilling operations. Just achieving a high penetration rate may not be considered economical if power consumption in operation is high. Power consumption can be minimized by controlling machine parameters such as bit rotational speed, load on bit, type of flushing media, and its concentration [Beste et al. 2007].

Friction at the interface of bit–rock and bit–hole sidewall (i.e. annular space) are the main sources of dynamic variation in power consumption. Frictional heat can influence the wear rate of the bits [Rao et al. 2002]. Approximately only 8% of the total energy consumed by a drill machine is utilized in the drilling process, and the rest is dissipated as frictional heat – mostly in the process of regrinding of drill cuttings. [Larson et al. 1987, Tutluoglu et al. 1983]

Water-based drilling fluids with polymeric additives have been used very commonly for solving the problems of drilling operation like filtration control, fluid loss, wellbore instability, shale recovery, etc. These polymeric additives are also having the property of lubricant to reduce the frictional and drag forces developed in the drilling operation. [Bhatnagar et al. 2010, Rao et al. 2002, Rawal et al. 2016].

2.8.3 Related to polymers

Carboxymethyl cellulose (CMC), guar gum (GG), and polyacrylamide (PAM) are water-soluble polymers. They have been found very common used as additives in the water to prepare drilling fluids in industries and research works [Alsabagh et al. 2014, Bhatnagar et al. 2010, Kelessidis et al. 2011, Pérez et al. 2004, Yadav et al. 2013]. The aqueous solution of these polymer additives are viscous in nature and also exhibits lubricating properties [Rawal et al. 2016].

The friction generated during drilling can be minimized with the help of the lubricating property of polymeric drilling fluids. Reducing the friction at the interface of the bit and sidewall of the hole, may reduce power consumption and improve the overall performance of the drilling operation. The effect of polymeric water-based drilling fluids in improving drilling efficiency was found to be effective in many studies [Alsabagh et al. 2014, Bhatnagar et al. 2010, Kelessidis et al. 2011, Rawal et al. 2011].

2.8.4 Related to Bit wearing

In drilling operation bit plays a vital role in rock penetration. In diamond bits, the diamond grits and bit matrix get worn out due to continuous wear and tear by the rock and drill cuttings while drilling a hole. While drilling with an impregnated diamond bit in hard rock, the performance of the drilling operation is influenced by the strength of the diamond grits and the matrix in which the diamond is fixed, [Bullen et al. 1979,1984]. The bit wear is the result of the wear advancement of the diamond grit and matrix [Kenda et al. 2009]. The worn diamond grit slides off the matrix and a new grit gets exposed. Hence, the performance of the diamond grits is the prime concern to determine the rock-breaking efficiency and working life of the bit [Yang et al. 2020].

The most influential factors for bit failure were diamond granularity and its concentration on the matrix. The cutting efficiency of a diamond grit decreases with granularity and increases with concentration. Whereas the wear resistance of grits increases with increasing granularity and concentration. Scholars have identified that the failure modes of impregnated bits while drilling in hard, and highly abrasive formations, are mainly diamond wear, shedding, and embrittlement [Yang et al. 2020].

Yang et al. (2020) have concluded that the drilling cost for highly abrasive rock strata is greater compared to the drilling cost for less abrasive strata. The responsible factors are frequent wearing of the bit, high wearing rates, low drilling efficiency, and premature failure cutting elements of the bit.

Various researchers have concluded that an impregnated bit is suitable for drilling in hard, compact, and abrasive formations like sandstone, and its breaking mechanism is equivalent to that of a grinding wheel [Jiang et al., 2009, Lin et al. 1994, Wang et al. 2017, Franca et al. 2015]. Compared with PDC bits and cone bits, impregnated diamond bits show better drilling performance in such formations [Lockwood et al. 2010, Mostofi et al. 2013, Zhu et al. 2019].

During drilling operation, the highest temperature in the whole drill string is attained by the bit because of the friction at the bit-rock interface. Due to this phenomenon, the bit becomes the most prone component to get worn out frequently in the drill system. Increasing frictional heat can accelerate the bit wearing [Rao et al. 2002]. The frequent wearing of the bit is directly associated with the additional involvement of money, time, and labor. It can be minimized by optimizing machine parameters i.e. rotation speed of bit, load on bit, and drilling fluid properties, etc.

Bit wearing is influenced by the combined effect of machine parameters (e.g. type & geometry of the cutting tool, penetration rate, and flushing media) and rock parameters (e.g. hardness, abrasiveness, quartz content, and texture). The overall efficiency of the drilling operation could get affected by the bit wearing and its associated problems. While drilling with healthy bit and normal working conditions, a large amount of total energy is wasted into frictional heat generated by the regrinding of drill cuttings, whereas only 8% of energy could be consumed in the actual drilling process [Larson et al. 1987, Tutluoglu et al. 1983].

Mainly four different types of wearing mechanisms work between two surfaces namely abrasive wear, fretting wear, adhesive wear, and surface fatigue [Machine 2021]. In drilling, rock cutting takes place by abrasive wear between bit and rock surface (i.e. wear between harder and softer surface). But the bit is worn out by fretting wear (repeated cyclical rubbing between two surfaces), adhesive wear (unwanted displacement and attachment of wear debris from one surface to another), and surface fatigue (cyclic loading of a surface).

With the help of proper flushing fluid, the bit wear can be reduced to achieve better drilling performance. Bit wearing reflected as 'loss in drillability of bit'. It can be measured in many ways such as by measuring loss in weight of bit, size & shape distortion, and loss of cutting elements, etc. Growth in the rate of drilling and enhancement in the efficiency of operation can be achieved by controlling bit wearing. To reduce bit wearing, many research groups suggested implementing a high-pressure water jet in rock drilling. [Fenn et al. 1989, Kim et al. 2012, Liu et al. 2015].

The role of a water jet in rock breaking during the rotary drilling process may have combined action of two different methodologies, which could be, (i) the expansion of pre-existing micro rock cracks, and (ii) weakening of rock by creating hydrostatic pressure at rock—jet interface. Among these methodologies, the first phenomenon seems more relevant for rock drilling with a small-scaled laboratory setup. The tensile stresses could be developed between the surface of preexisting micro-cracks by the flow of drilling fluid and weaken the influenced rock surface. These expansion cracks may follow the opening mode of fracture mechanics in which the tensile stress acts normal to the plane of the crack [Gryc et al. 2014]. The weakened rock could save the health of bit or reduce bit wearing by reducing the required efforts in achieving the desired hole depth. Roderick et al. (2004), had experimented with the water as flushing fluid in the blast hole drilling and found that water helped in reducing bit wear, hole deviation, and increase the rate of penetration (ROP).

2.8.5 Related to Bit Vibration

The vibration in the drill machine has many adverse impacts on overall performance. Saldivar et al. (2014), has classified the vibrations generated during drilling operation in three major categories namely torsional (stick-slip), axial (bit-bounce), and lateral (whirling). Jafari et al. (2012), have studied the effect of load on bit and fluid flow rate on the vibration of the drill string. Whereas It was found that increasing both individually, may be led to decreasing of natural frequencies of vibration in the drill string. Saasen et al. (2016), have concluded that the highly viscous drilling fluids are less affected by vibration due to strong gel structure. An investigation was conducted by Eski et al. (2012), focused on designing a robust neural network predictor for analyzing vibration effects on drilling machines components. On the basis of the literature discussed, the present research work was planned and executed to achieve the objectives.