New Hampshire DOT Research

Use of Drilling Parameters for Enhancing Geotechnical Site Investigations with Applications to Rock Assessment

Final Report

Prepared by University of New Hampshire Department of Civil and Environmental Engineering, College of Engineering and Physical Sciences, in cooperation with the U.S. Department of Transportation, Federal Highway Administration

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16. Abstract

This report summarizes the research conducted using Measurement While Drilling (MWD) technology that was recently implemented as part of routine geotechnical investigations conducted by the New Hampshire Department of Transportation (NHDOT). MWD is a system that consists of several sensors directly mounted or connected to a drill rig to monitor all aspects of geotechnical borehole drilling. These sensors record advance rate, rotation rate, downthrust (pressure and force), torque, water/mud flow, water/mud pressure, and vibration. These measurements are obtained in real-time at vertical intervals of 5 cm without interfering with routine drilling operations. Equipment setup on an NHDOT drill, test procedures, and data collection methods were iteratively refined throughout an experimental campaign across 14 sites, comprising a total of approximately 40 boreholes. MWD profiles were analyzed in conjunction with conventional methods such as the Standard Penetration Tests (SPT), the Piezocone, and Rock Quality Designation (RQD) to evaluate their effectiveness in delineating stratigraphic transitions and interpreting subsurface conditions. Results demonstrated that MWD data can provide valuable insights into subsurface variability, soil and rock types, presence of fractures, as well as potential for correlations with geotechnical properties. MWD offered a continuous representation of drilling conditions that enhanced site characterization beyond the discrete sampling offered by tests such as the SPT. Lessons learned during the study highlight the importance of integrating additional site-specific information, such as drill bit type, operator-controlled drilling adjustments, and soil cuttings observations to enhance data interpretation. Additionally, challenges in data collection and analysis highlight the need for standardized procedures to improve the consistency and usability of MWD data.

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DISCLAIMER

USE OF DRILLING PARAMETERS FOR ENHANCING GEOTECHNICAL SITE INVESTIGATIONS WITH APPLICATIONS TO ROCK ASSESSMENT

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FINAL REPORT

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EXECUTIVE SUMMARY

This report summarizes the research conducted using the Measurement While Drilling (MWD) technology to support subsurface investigations by the New Hampshire Department of Transportation. The work performed by the University of New Hampshire, in collaboration with the NHDOT Geological Exploration team, consisted of the installation of an MWD system on one of the NHDOT drill rigs with torque measurement and field evaluation of MWD through testing at various sites across New Hampshire. MWD is a system that consists of several sensors directly mounted or connected to the NHDOT drill rig to monitor all aspects of geotechnical borehole drilling used in routine site investigations. These sensors record advance rate, rotation rate, downthrust (pressure and force), torque, water/mud flow, water/mud pressure, and vibration. These measurements are obtained in real-time at vertical intervals of 5 cm without interfering with routine drilling operations.

The latest MWD equipment and test procedures were gradually adapted and improved over an extensive field campaign including approximately 40 boreholes conducted at 16 different NHDOT sites with a wide range of geological conditions. MWD measurements were used to evaluate subsurface conditions and were compared to field logs and results from conventional geotechnical testing such as the Standard Penetration Test (SPT) and the piezocone (CPTu), as well as comparison to Rock Quality Designation (RQD) when coring in bedrock.

The findings of this study confirm that Measurement While Drilling systems can greatly enhance site characterization continuously and in real-time, during boring advance in geological profiles typically encountered at sites in New Hampshire. It was demonstrated that MWD profiles are particularly helpful in delineating changes in stratigraphy, leading to more accurate geotechnical models essential in projects such as bridge foundation design. In parallel to the conventional MWD system, this research also assessed a prototype for a portable MWD, which presents a high potential for subsurface assessments at shallow depths.

The present report introduces the latest MWD equipment, discusses the most relevant results from this experimental campaign, and demonstrates how MWD relates to results from conventional geotechnical tests. A comprehensive test method and instructions for data analysis were also included for future testing by the NHDOT in their routine site characterization operations.

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1. INTRODUCTION

The Standard Penetration Test (SPT – ASTM D1586) is a proven tool widely used in providing disturbed soil samples to aid in geotechnical site characterization for the design of New Hampshire Department of Transportation (NHDOT) projects. In addition to collecting soil samples that allow delineating site stratigraphy and for index property testing, SPT tests also provide profiles of soil resistance to penetration as a function of depth. Although this test method is still extensively used in current geotechnical practice in the United States, the method is deemed unreliable because of the numerous uncertainties associated with the test method (Holtrigter, 2023). SPT testing is also time-consuming, labor intensive, and not applicable in all geological conditions, such as gravelly soils and rock. The SPT is typically carried out continuously or at 5-to-10-foot intervals. In addition, in soils containing clean sand, gravel, or rock fragments, the sample recovery is often below 50%, which further reduces the reliability of the test method. Such gaps in recovered samples and the intervals between tests often lead to unreliable geological profiling.

The cone penetration test (CPT) is often proposed as an alternative for continuous and rapid soil stratigraphy profiling. However, this test method offers substantial resistance to penetration on very hard or stiff ground, as well as soils containing large particles such as gravel. The required penetration force to advance the cone penetrometer is often beyond the capability of standard geotechnical drilling rigs, necessitating specialized cone penetration trucks that are not well-designed to access remote and soft ground locations.

In response to these drawbacks, a technique known as Measurement While Drilling (MWD) has been increasingly promoted as an exploration tool based on the ground response from the imposed drilling method. MWD records all aspects of drilling in real-time, including the advance rate, rotation rate, downthrust, torque, water/mud flow and pressure. When combined with other geotechnical test methods, such as the SPT or the CPT, MWD profiles present a high potential to accurately represent subsurface conditions without interfering with normal drilling operations (Reiffsteck et al., 2018), leading to more accurate geotechnical models to be used for safer and more economical designs. The test is currently standardized by the European standard ISO 22476-15:2016. However, information on testing procedures and recommendations for data reduction is still limited and imprecise in these standards. As a result, the current version of ISO 22476-15 cannot be used as a guide for implementing MWD. A separate AASHTO standard is being developed to facilitate technology diffusion and provide guidance for using MWD in geotechnical investigations.

Although interest in MWD has significantly increased in recent years, the Federal Highway Administration EDC-5: Advanced Geotechnical Methods in Exploration (A-GaME) initiative still recognizes it as an underutilized site characterization tool. The research described in this report helped develop tools and methods to advance the use of MWD in geotechnical site characterizations performed by the NHDOT. It introduces the latest MWD technology and describes the use of the equipment as well as provides data analysis tools to help generate geotechnical profiles to complement those obtained by standard test methods.

1.1. Objectives

The general objective of this research was to implement and integrate Measurement While Drilling into subsurface investigation practices as an additional evaluation tool for the New Hampshire Department of Transportation. The specific objectives of this research project were defined as follows.

- To fully instrument an NHDOT drill rig with the latest Measurement While Drilling equipment.
- To provide MWD as a tool for geotechnical site characterization for a more accurate representation of subsurface conditions.
- To rapidly identify the bedrock depth for mapping efforts and water quality studies.
- To objectively assess bedrock quality for foundation and water quality studies and rock slope stability efforts.
- To collaborate with current and prospective MWD users nationwide and worldwide.

This report describes how these objectives were met through experiments and analyses conducted by the University of New Hampshire.

1.2. Scope of work

The work performed in this research project consisted of the following tasks:

- *Task 1* – Update the existing UNH MWD system with the latest equipment.
- *Task 2* – Install the newly purchased MWD system on one of the NHDOT drill rigs.
- *Task 3* – Purchase and install a torque sensor to be fitted to the mechanically driven drill rig operated by the NHDOT.
- *Task 4* – Perform MWD boreholes in NHDOT job sites in parallel with SPT tests and rock coring performed at adjacent boreholes.
- *Task 5* – Evaluate the MWD data obtained with conventional geotechnical tests.
- *Task 6* – Collaborate with other MWD users and prospect users across the U.S. and worldwide.

- *Task 7* – Provide a final report summarizing the research and providing recommendations for implementing the MWD in everyday sites and soil exploration.

This report summarizes the work performed to accomplish the various tasks required for this research project.

2. MWD EQUIPMENT

2.1. MWD History

Initially developed for use in the oil industry in the 1960s, the recording of parameters during the drilling process was used to control or correct a borehole to reach target locations at depth in the subsurface. Adaptions and improvements to MWD (originally referred to as Drilling Parameter Recording or DPR) have been made in the geotechnical field since the 1970s, especially in Europe and Japan. Since then, MWD has been used routinely in Europe to monitor drilling operations, characterize the subsurface stratigraphy, detect fractures and cavities, and assist in foundations, grouting in soils, and tunneling stabilization projects (Sadkowski, 2004).

The MWD equipment consists of computerized systems monitoring a series of transducers installed on conventional drilling rigs. The first recorders were analog (Figure 2.1a) and provided a graphical output on a single paper strip with up to four parameters: advance rate, rotation rate, downthrust, and drilling fluid pressure (Pfister, 1985). In the early 1980s, these systems were updated to record parameters digitally, which increased the number of recorded parameters, improved precision, and generated digital files for post-treatment processing (Girard et al., 1986). As boreholes were drilled, operators could monitor up to eight recorded parameters on a strip chart printed in real-time, along with real-time outputs of up to eight parameters on an LCD screen: advance rate, rotation rate, torque, downthrust, drilling fluid flow, drilling fluid pressure, holdback pressure, and vibration (Figure 2.1b). More recently, MWD has seen further improvements with rugged, waterproof tablets (Figure 2.1c), where test calibrations, settings, and changes in data display can be easily performed on user-friendly interfaces with capabilities to share data using Wi-Fi.

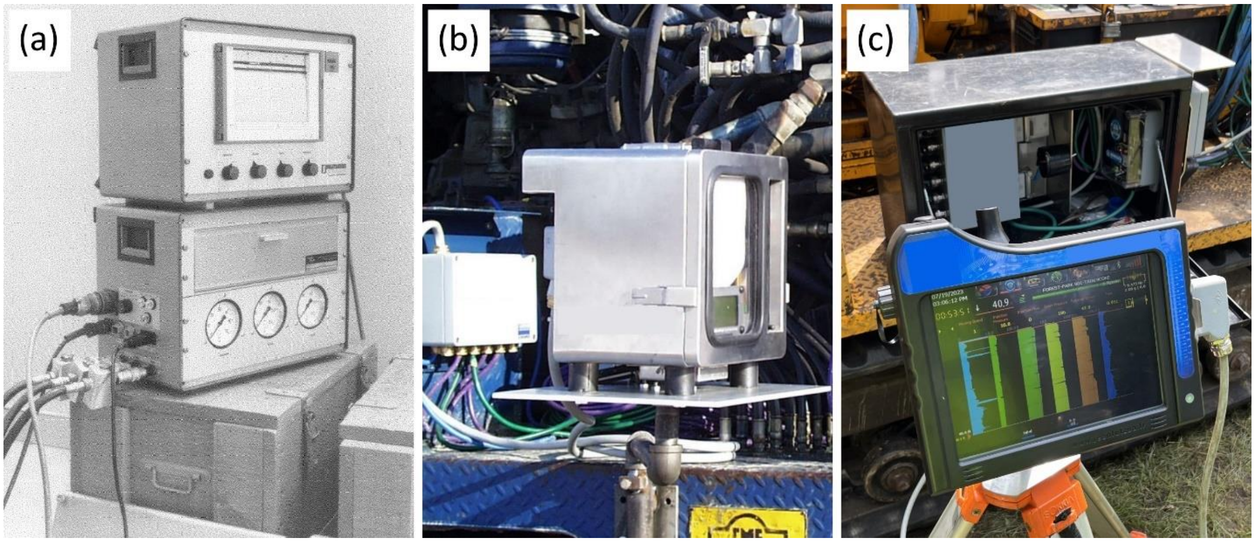


Figure 2.1. Evolution of MWD: (a) Analog DPR (Enpasol method, 1976); (b) digital MWD with LCD screen; and (c) digital MWD with waterproof tablet.

2.2.Description of test and support equipment

Table 2.1 lists the parameters that can be measured during MWD along with the units listed in the European standard and upcoming US standard, as well as their corresponding conversions. This section also describes the MWD sensors and their respective measured parameters. Instrumentation for monitoring drilling parameters is now available from several suppliers, and this report limits equipment description to the sensors employed in this research which have been purchased from Jean Lutz (JL) and MWD One. All test instrumentation was installed on a CME-45C truck-mounted mechanical drill rig used in routine NHDOT operations, as shown in Figure 2.2.

Table 2.1. List of drilling parameters and their respective units.

Drilling parameter	Units		
	Default Jean Lutz software	**Upcoming US standards and conversion factor**	**European standards and conversion factor**
Depth (d)	m	0.3048 ft	m
Drilling rate (u)	m/h	0.01667 in/min	m/h
Thrust pressure (Pe)	bar	14.50 psi	0.1 MPa
Thrust force (Fe)	N	0.225 lbs	0.001 kN
Rotation rate (Vr)	RPM	RPM	RPM
Torque (T)	N-m	8.85 lbs-in	0.001 kN-m
Vibration frequency (f)	Hz	Hz	Hz
Vibration acceleration (G)	m/s²	0.3048 ft/s²	m/s²
Drilling fluid pressure (P)	bar	14.50 psi	0.1 MPa
Drilling fluid flow rate (Qi)	L/min	3.78 GPM	L/min

Figure 2.2. Measurement While Drilling Equipment at the New Hampshire Department of Transportation, USA.

The newest Jean Lutz system was selected in this research project because it is compatible with equipment already in use by the University of New Hampshire from an earlier version of the JL MWD system. The new JL MWD system (except for the torque sensor) shown in Figure 2.2 was purchased and installed in May 2021. Preliminary testing in Merrimack and Dover, NH, followed the equipment installation in the Summer of 2021. Since then, several improvements have been made, as summarized in this report.

Although the JL system was designed to record all parameters described in Table 2.1, the test equipment presents a major limitation in measuring torque since it was initially designed for hydraulic drill rigs. As a result, the installed equipment consisted of all sensors except for the wireless torque sensor, presented in Figure 2.2f(I), which was installed at a later stage of this research.

2.2.1. Junction box, data logger, and PI box

The sensors included in the Jean Lutz system consisted of wired sensors that are directly connected to a junction box (Figure 2.2a). The output from the various sensors is relayed to a data logger (Figure 2.2b), which consists of a rugged, weatherproof computer tablet. The logger controls all testing phases, considering the various calibration factors for each sensor. Measurements from all wired sensors are directly stored in the data logger. In contrast, measurements from the wireless torque sensor are initially gathered by a PI Box (Figure 2.2c), which communicates directly with the data logger in Figure 2.2b. The raw data files are exported through a USB port in the data logger. Data processing can be performed using the JL software, Excel, or MATLAB.

The data logger screen can be wirelessly transmitted to any computer to allow real-time remote monitoring or to assist in troubleshooting field issues. Each drilling parameter is internally measured by the system as a function of time at a sampling frequency of 8 kHz. For data visualization and processing, the user can select the depth recording step, which graphs to be displayed, and which tabulated data to be exported. By default, the Jean Lutz equipment recommends a 2 cm (0.8 inch) recording step, at which all data sampled over a single depth increment will be averaged and displayed as a function of depth rather than time. Therefore, while the data is internally sampled at a fixed frequency (regular time increments), the output data will be generated at regular depth increments (irregular time increments).

The upcoming US standards recommend minimum data recording frequency requirements for different depth increments and desired levels of accuracy. For a recorded depth increment of 1 inch (quality class 1), a minimum measurement frequency of 100 Hz would be required. However, given that the equipment used in this research project records data as a function of the drilled depth, regular sampling intervals are not provided as a function of time. Therefore, the sampling frequency on the Jean Lutz equipment depends directly on the penetration rate and, thus, the geological material being drilled through.

2.2.2. Depth and advance rate

The drilled depth is measured using a linear displacement sensor (Figure 2.2i) mounted on the drill rig mast. It consists of a pulley assembly fixed on the drill mast and connected to the drill head. As the drilled depth advances, the internal potentiometer varies the output voltage calibrated to a length measurement. The internal system clock in the data logger records the measurement time and calculates the penetration rate. The recorder monitors all movements of the drill string but only records data for new advancing depths, allowing the driller to move up and down the borehole without interfering with the measurements. However, the data for all aspects of drilling are recorded internally with time and can accessed by the user if necessary.

2.2.3. Downthrust pressure

The downthrust pressure or crowd imposed by the driller can be visually monitored using the pressure gauge installed on the drill rig and by the MWD system through the use of a pressure transducer shown in Figure 2.2d, installed in the hydraulic pressure line near the rig gauge on the control panel. The installation requires a T-connector to tap into the hydraulic line.

The downthrust recorded using the pressure transducer must be corrected for the idling or baseline rig pressure. To determine the actual down force, the pressure needs to be converted to force by taking into account the area of the piston cylinders (6.8 in.² for the CME 45C used by the NHDOT) and to take into account the weight of the drill string as the borehole is advanced into the subsurface (e.g. 29 lbs for each 5-ft NWJ rod), as shown in Equation 2.1.

$$Pe = \{(Pe_{measured} - Pe_{baseline}) * 6.8\ in^2 + (depth * 29\ lbs\ /\ 5\ ft)\}\ /A_{drill\ bit} \quad (2.1)$$

Where: Pe = corrected downthrust pressure (psi)

$Pe_{measured}$ = downthrust pressure from the pressure transducer (psi) = gauge pressure

$Pe_{baseline}$ = baseline reading before the beginning of the test (psi)

$A_{drill\ bit}$ = area of the drill bit used (in²)

$depth$ = current depth measurement for the given downthrust pressure (ft)

2.2.4. Rotation rate

The rotation rate is measured through a proximity sensor attached to a plate near a set of evenly spaced welded studs on the rotating shaft. The proximity sensor detects each stud (Figure 2.2g) as it passes in front of the sensor and calculates the rotation rate in RPM based on the number of studs per time. For the CME 45C rig, 8 studs were used for each rotation. The number of welded studs is directly inputted in the data logger by the user, and the measurement accuracy can be easily verified through visual inspection by counting the number of rotations over a known time (e.g., one minute) or directly measured with a tachometer.

2.2.5. Torque

Since the torque cannot be measured in mechanical drill rigs using hydraulic pressure transducers, the initially installed equipment could not measure the torque during drilling operations until the first wireless torque sensors were successfully developed (May 2021) and commercialized in July 2023. Until then, MWD measurements performed on mechanical rigs provided useful but limited information on drilling since torque is an important component in data interpretation and is required in drilling energy calculations.

- Torque sensor design

Previous efforts to estimate torque from hydraulic drill rigs were done using hydraulic sensors with knowledge of the gear used for each depth, along with efficiency charts provided by drilling manufacturers. For mechanical drill rigs, prototypes of torque measurement devices were introduced in the early 2020s with either load cells mounted at the top of the drill string or with instrumented drive shafts (Rodgers et al., 2020; Caplane et al., 2024). Therefore, designing or implementing a torque sensor for the MWD system was one of the main tasks of this research project.

A wireless sensor was required to measure torque directly at the top of the drill string. Between the initial equipment acquisition (May 2021) and the first successful torque measurements (July 2023), UNH and the NHDOT made significant efforts to find an effective solution. After careful analysis, it was decided to purchase a wireless torque sensor.

Due to the required compatibility between the wireless torque sensor and the previously installed Jean Lutz data logger, we initially opted to test the TICOR sensor developed by Jean

Lutz. The TICOR sensor was designed to measure torque, downforce, and rotation rate. The device was initially delivered to the NHDOT in November 2022. After an initial attempt to use the TICOR, communication issues were identified between the device and the data logger. The sensor was then repaired and delivered back to UNH in May 2023. The sensor was re-installed in June 2023, and additional tests were performed in Durham/NH in July to implement the sensor in MWD operations. We communicated with Jean Lutz and identified that the sensor was still not fully operational, with issues in the load cell that measures the downforce. The TICOR was shipped back to Jean Lutz, France, in September 2023 for further repairs.

In light of these setbacks and the recent development of a torque sensor by Dr. Michael Rodgers (MWD One), an instrumented drill rod compatible with the Jean Lutz equipment was acquired in July 2023. Torque measurements from TICOR and MWD One in Durham/NH were compared, and the data from both sensors at adjacent boreholes were compatible, although the MWD One sensor was more compact and easier to use. After our initial evaluation of the instrumented drill rod by MWD One, the NHDOT purchased a second unit that wirelessly measured the torque and thrust at the top of the drill string. The new sensor was tested in November 2023 in Loudon/NH. Similar to the previous torque sensor by MWD One, the new sensor also easily communicates with the Jean Lutz system already in place.

The MWD One instrumented rod is shown in Figure 2.2f(I) and consists of an AWJ rod 2 ft long, with torque rosettes and T-element strain gauges placed every 90° over the device's circumference to measure the downthrust. A wireless data transmitter communicates with an auxiliary junction box into the main junction box. The system was calibrated to perform with the JL system and ensure accurate torque and thrust force measurements (Rodgers et al., 2020). Two additional instrumented rods were recently purchased as part of the MWD instrumentation for the newly acquired CME-55 drill rig.

2.2.6. Drilling fluid (water) flow and pressure

Drilling fluid to assist drilling operations has traditionally been water for most boreholes drilled by the NHDOT. A water truck is used for that purpose, and it typically requires refilling during the day, depending on the geological material to be drilled. Water was the only drilling fluid used in this experimental campaign in drilling and coring operations. The inflow is measured with an electromagnetic flowmeter attached downstream of the drill rig pump, as shown in Figure 2.2h. The flowmeter records flow through electronic pulses and consequently can handle mud or water used as drill fluid. The driller directly controls the inflow with a valve to ensure efficient cuttings removal and reduce wear of the drill bit when coring rock (Sadkowski, 2004). However, without the MWD instrumentation, precise information on the flow rate is not available. In addition to the inflow, a second flowmeter can be installed at that outflow to provide information on the fluid lost in the subsurface (fluid lost = inflow – outflow). Measuring the net flow is especially useful in detecting cavities, fractures, or very porous geological material (Sadkowski et al., 2008). UNH has recently purchased an additional flowmeter to measure the outflow in future drilling operations. The NHDOT will also use mud tubs to reduce water consumption and provide better visual information on the formation being drilled by observing cuttings continuously while advancing a borehole.

While the operator controls the injection flow, the injection pressure is measured with a pressure transducer attached using a T-connector along the drilling fluid pressure line located downstream from the water pump. Although this parameter is not used in drilling energy calculations, it is a strong indicator of possible blockages or drilling fluid loss, which can help identify certain geological features and improve the quality of the resulting borehole. Generally, cavities (voids and fractures) and porous zones are typically associated with decreased water pressure. At the same time, cohesive materials where bit clogging may occur if inadequate flow and/or advance rates are too rapid, an increase in fluid pressure is typically observed.

2.2.7. Vibration

The vibration experienced by the drill rig while drilling different geological materials is quantified through an accelerometer installed near the top of the drill string, as shown in Figure 2.2f(II). The vibration sensor depicts two variables: the vibration, measured as a function of the gravitational constant ($g = 32.2$ ft/s^2), and the vibration frequency, measured in Hz. Although measurements using the vibration sensor will vary based on where it is installed on the drill rig, there is significant potential to use both frequency and acceleration as indicators of strata changes and the presence of rock fragments and gravel in soils.

2.3. Categories of drilling parameters

Although several studies have been performed on rock, there is still a lack of MWD data on different soil types and comparisons between other methods for soil characterization in situ. The complexity of data interpretation is significant, as it is still not well-understood how changes in drilling parameters can be associated with material types. The complexity of data interpretation is even higher considering that parameters imposed by the drilling method (e.g., tool type and diameter, performance limits of the drill rig, fluid injection system, and fluid type) can lead to significant differences in measurements (Cailleux, 1986; Reiffsteck et al., 2018). Cailleux (1986) characterizes the drilling parameters defined in the previous section into four categories:

1) <u>Imposed by the drilling method but not digitally recorded (tool type and diameter, performance limits of the drill rig, fluid injection system, and fluid type)</u>

The experimental campaign presented in this report was performed with a single drill rig, thus leading to identical conditions in terms of rig performance and fluid injection system. All tests were performed using water as drilling fluid.

Discussions were initially made between UNH and the NHDOT in terms of the drilling tool and diameter that should be used in this experimental research. Initial trials (before the torque sensor installation) were performed with a 2.2-in. diameter tricone steel roller bit, shown in Figure 2.3, which, according to the Australian Drilling Industry Association (ADITC, 2015), is recommended for medium formations, which do not comprise geological materials of high compressive strength such as bedrock.

An initial evaluation of the steel roller bit in preliminary boreholes demonstrated that this drilling tool was easily subjected to wear and, at times, completely worn off while drilling a single shallow borehole. Figure 2.3 presents the wear of an initially brand-new drilling tool after drilling 30 ft in glacial deposits at a bridge construction site in Orford, NH. Given that the effect of tool wear, to date, cannot be objectively quantified in MWD assessments, it was opted to select another drilling tool that would be less subject to wear and more resistant to the geological materials typically encountered in New England. The NHDOT then replaced the steel tricone roller bit, recommended for medium formations, with a 2.8-in. diameter carbide hard formation button roller bit (Figure 2.4). Hard formation bits were designed to resist higher compressive strength while withstanding higher abrasiveness. Carbide was selected since they can hold their shape better than steel-toothed bits (ADITC, 2015).

Figure 2.3. Wear on a 2.2-in. tricone steel roller bit after drilling 30 ft in a glacial deposit in Orford, NH. The tool on the left is a new bit of the same make and model.

Previous field MWD assessments performed by Reiffsteck et al. (2018) evaluated different drilling tool types (bicone roller bit, drag bit, cross bit, button bit, and continuous flight auger). They observed that the type of tool is an important factor and plays a key role in measured drilling parameters. However, this effect is, to date, not quantified, and there is a lack of empirical relationships to standardize drilling parameters based on the tool used to advance a borehole. Therefore, to reduce uncertainties associated with tool type in this experimental campaign, the carbide button roller bit, commonly used in NHDOT projects, was selected as the only tool type used in this experimental program.

2) <u>Controlled by the driller (thrust on the drill bit, rotation rate, drilling fluid flow rate)</u>

Although the driller controls these drilling parameters, limited information is provided to the test operator without an MWD system. While the downthrust can be estimated based on the gauge reading, accurate measurements of the rotation rate and fluid injection rate are not feasible. Therefore, these parameters are controlled by adjusting the throttle (rotation) and valve (flow). Thus, typical ranges of drilling parameters at which drilling and/or rock coring is more efficient cannot be determined without an external instrumentation system such as MWD (Rodgers et al., 2018b).

3) A response to ground conditions (advance rate, torque, fluid injection pressure)

In routine MWD drilling operations, the parameters controlled by the driller (thrust, rotation, inflow) are kept relatively constant, while variations of other parameters (response to ground conditions), such as penetration rate, torque, and drilling fluid pressure, are observed as the borehole progresses through various layers of soil and rock.

4) Not controlled (tool wear, changes in drilling fluid composition)

Based on experimental results by Reiffsteck et al. (2018), new or sharpened drill bits led to more energy-efficient drilling due to a smaller contact area against the ground. In this context, the aim was to minimize tool wear while drilling to avoid uncertainties related to tool wear. After the change in the drilling tool for the carbide button roller bit recommended for hard formations, minimal tool wear was observed during the entire experimental campaign, as shown in Figure 2.4.

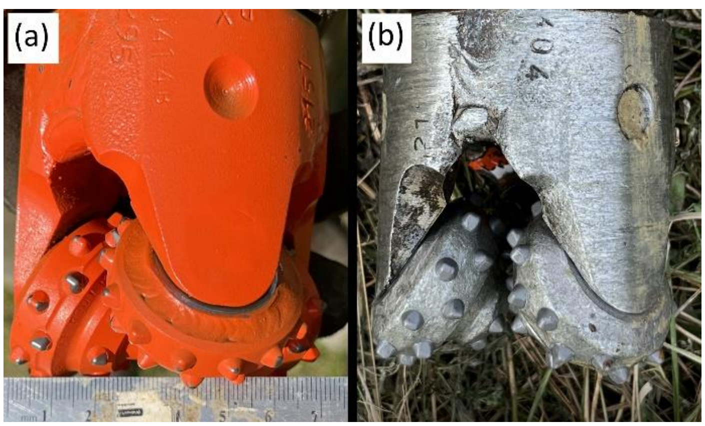


Figure 2.4. 2.8-in. diameter tricone carbide drill bit used in the experimental campaigns (a) before and (b) after tests – no significant wear.

3. MWD DATA REDUCTION

3.1. Compound drilling parameters

Given the number of measured variables in each MWD profile and the uncertainty of which parameters or combinations of parameters, different compound parameters were evaluated to develop empirical relationships between conventional geotechnical properties and MWD measurements. Some of these parameters, detailed in Equations 4.1 to 4.6, consist of empirical indices or energies that combine two or more drilling parameters to reflect the material's resistance to drilling. Although changes in drilling parameters often indicate changes in subsurface conditions, compound parameters attempt to normalize the effect of conditions imposed by the driller, e.g., rotation rate and downthrust. Such normalization effort is indispensable to evaluate large data sets and establish comparisons between different sites, even if the same test operator performed all tests.

Some compound parameters require the downforce (Fe) or crowd to estimate drilling energy. This downforce can be estimated using the hydraulic pressure measured by the Jean Lutz sensors by considering the hydraulic piston areas to calculate the applied thrust, as previously discussed in Section 2. However, a more accurate measure of thrust can now be achieved using sensors mounted directly at the top of the drill string. This type of sensor was acquired from MWD One, consisting of an instrumented rod designed to simultaneously measure both torque and thrust force. The thrust force (Fe) can then be transformed into pressure (Pe), as shown in Equation 3.1. Equations 3.1 and 3.2 allow a direct comparison between crowd pressure measured by the hydraulic pressure sensor and the calculated pressure from the direct measurement of downforce from the instrumented rod.

$$Pe = Fe/A_{drill\ bit} \tag{3.1}$$

$$Pe = ((Pe_{measured} - Pe_{baseline}) * 6.8\ in.^2 + depth * 29\ lbs/5\ ft)/A_{drill\ bit} \qquad (3.2)$$

Where: Pe = net downthrust pressure (psi)

Fe = net downthrust force (lbs) measured by the instrumented rod (MWD One)

$A_{drill\ bit}$ = drill bit area (in.^{2})

$Pe_{measured}$ = downthrust pressure from the pressure transducer (psi) = gauge pressure

$Pe_{baseline}$ = baseline reading before the beginning of the test (psi)

$depth$ = current depth measurement for the given downthrust pressure (ft)

It is important to highlight that *Pe* corresponds to the ***net*** downthrust pressure, which corresponds to the downthrust pressure when a holdback pressure is not applied. When a holdback pressure is applied, it is necessary to subtract the holdback pressure from the downthrust pressure to obtain the net pressure, *Pe* (net = downthrust – holdback). This operation is not necessary when using the instrumented rod as it directly measures the actual applied force.

3.1.1. Somerton Index

The Somerton Index (Equation 3.3 – Somerton, 1959, modified by Girard, 1985) is an empirical index that characterizes the drilling resistance of a material. Somerton introduced his index using some of the parameters that controlled the rate of bit penetration in rock and concrete. The index is based on the total weight on the bit (lb), penetration rate (in./min), rotation rate (rpm), and bit diameter (in.). The Somerton Index from his original paper is then given in units of lbs/in.^{2} Since then, the equation introduced by Somerton has been modified by Girard (1985), leading to an expression with inconsistent units instead of unitless. It is important to highlight that the units recommended by the European and US standards do not present equivalent unit conversions. Thus, Sd values should not be used interchangeably between different unit systems as it will lead to inaccurate interpretations. Attention must also be given to previously published data and empirical relationships in the literature, mostly calculated following the SI units recommended by the ISO standards, even though they list the Index as being unitless. The current equation, referred to as the Somerton index and shown in Equation 3.3, employs the units proposed by the draft AASHTO standard. In order to evaluate the effect of other drilling parameters, it is usually recommended to keep the rotation rate constant within the full profile or for each geological material.

$$Sd = Pe * (N/u)^{0.5} \tag{3.3}$$

Where: Sd = Somerton Index (provided without units)

Pe = net downthrust pressure (psi)

N= rotation rate (RPM)

u = advance rate (in./min)

3.1.2. Drilling energy

The energy to drill shallow boreholes was first introduced by Teale (1965) and later modified by Pfister (1985), as shown in Equation 3.4. Pfister (1985) suggested a simplification where the thrust pressure is neglected and only the work produced by the torque is considered, as shown in Equation 3.5. However, although the ISO standards recommend both equations, the US standards only recommend using Equation 3.4. Research by Rodgers et al. (2021) suggests that the thrust component of the energy equation by Teale only accounts for less than 0.5% of the total specific energy from a series of controlled tests in Florida limestone.

$$e = Pe + (2 * \pi * N * T)/(A_{drill\,bit} * u) \tag{3.4}$$

$$e_R = (2 * \pi * N * T)/(A_{drill\,bit} * u) \tag{3.5}$$

Where: e = specific drilling energy (psi)

e_R = drilling energy by rotation torque (psi)

Pe = net downthrust pressure (psi)

N = rotation rate (RPM)

T = torque (lbs-in.)

$A_{drill\ bit}$ = drill bit area (in.^{2})

u = advance rate (in./min)

3.1.3. Penetration resistance

The penetration resistance (ISO 22476-15:2016) was also calculated for each time step (Equation 3.6). It consists of the time in seconds for a given penetration depth. The European standards recommend a depth of 0.20 m, but the depth recommended by the upcoming US standard was chosen to be 0.025 m (1 inch) instead. This parameter is most effective when the thrust pressure is kept constant with depth.

$$P_R = (time)_{Z\,=\,1\ in.} \tag{3.6}$$

Where P_R = penetration resistance

3.1.4. Sample calculations

This section presents sample calculations for the introduced compound parameters, considering the following measurements at a given depth:

Drilling rate: u = 25 in./min

Net downthrust pressure: Pe = 250 psi

Torque: T = 500 in.-kips

Rotation rate: N = 120 RPM

Drill bit area: $A_{drill\ bit}$ = 5.98 in.^{2}

- Somerton index

$$Sd = Pe * \left(\frac{N}{u}\right)^{0.5} \therefore Sd = 250\,\frac{lbs}{in^2} * \left(\frac{120\ RPM}{25\ in./min}\right)^{0.5} = 547\ (unitless)$$

- Drilling energy

$$e = Pe + \frac{2*\pi*N*T}{A_{drill\ bit}*u} \therefore 250\,\frac{lbs}{in^2} + \frac{2*\pi*120\ RPM*500\ in-lbs}{5.98\ in^2*25\ in/min} = 2772\ psi$$

$$e_R = \frac{2*\pi*N*T}{A_{drill\ bit}*u} \therefore e_R = \frac{2*\pi*120\ RPM*500\ in-lbs}{5.98\ in^2*25\ in/min} = 2521\ psi$$

- Penetration resistance

$$P_R = (time)_{Z\,=\,1\ in.} = \frac{1}{i} = \frac{1}{25\ in/min} = 0.04\ min = 2.4\ s$$

3.2. Data reduction procedure

For the detailed procedure on preparing the equipment for testing and performing an MWD test, the reader is referred to Appendix A – MWD testing procedure. Once the MWD file has been recorded and downloaded after a test, data must be first exported using the Jean Lutz software and then processed using readily available software such as Excel, MATLAB, or the Jean Lutz software. The detailed procedure for exporting and processing MWD data saved in a USB drive is presented as follows:

a) Exporting the raw data spreadsheet

i. Each MWD test generates a Jean Lutz .FDL file, which must initially be opened using the Jean Lutz software – EXEPF.

ii. Drag the raw test file to the EXEPF main screen. The test data will be graphically displayed on the main screen.

iii. Under 1. Drill, select 1.3. Import/export text and then select 1.3b Text export (Figure 4.1).

iv. A new window will appear (Figure 3.1, right side). Select ".xlsx file" under format and click OK. A Microsoft Excel spreadsheet with all drilling data at approximately 2 to 3 cm depth intervals will open automatically. Please pay attention to the units; the data will be exported in SI units.

v. Select the data columns corresponding to drill depth, advance rate, downthrust pressure (uncorrected pressure from JL sensor), downthrust force, rotation rate, torque, frequency, acceleration, water flow, and water pressure. Copy and paste the data into a second Excel file (created by the user), as shown in Table 3.1.

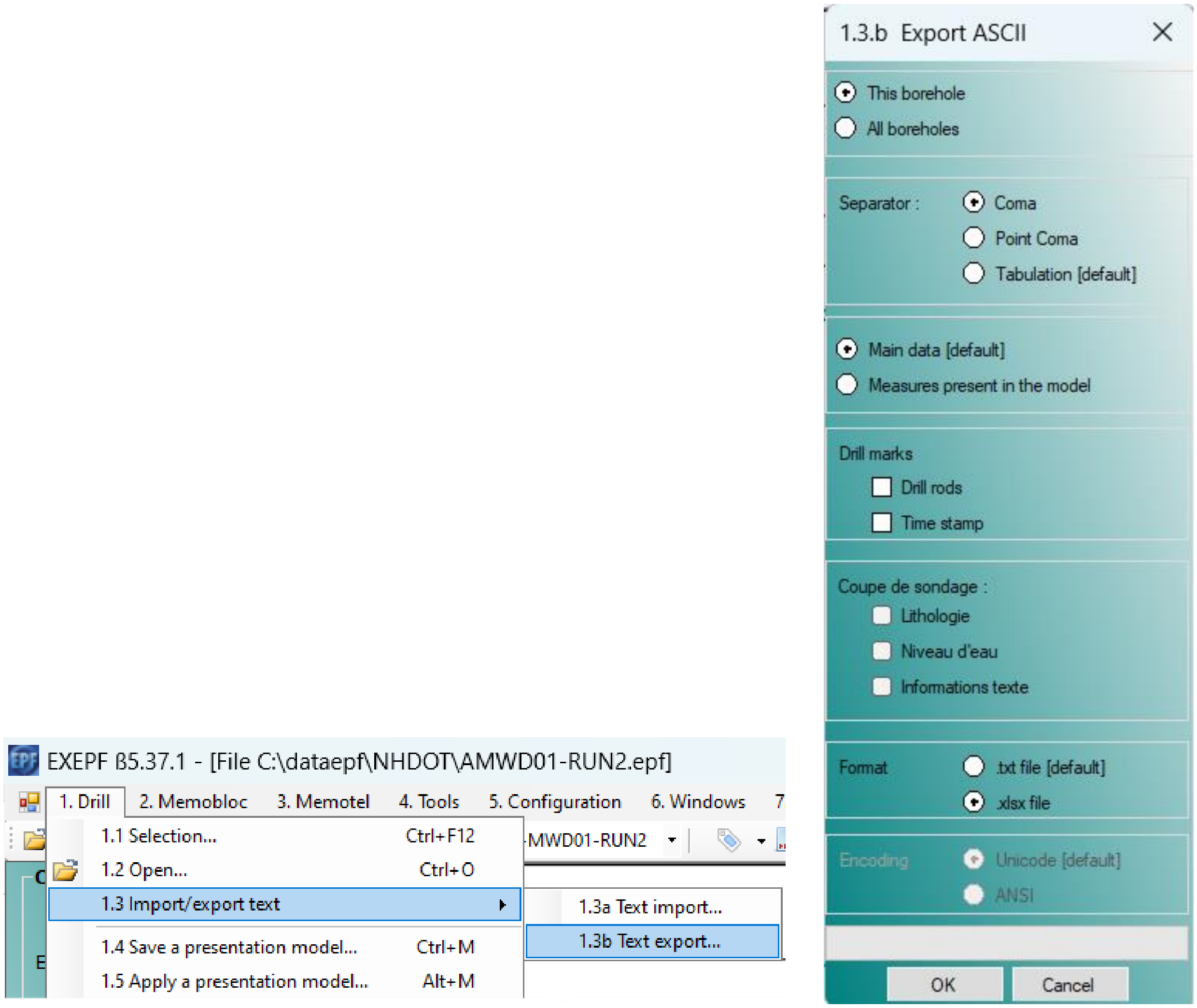


Figure 3.1. Exporting raw .FDL data files generated by the Jean Lutz data logger.

Table 3.1. Sample raw data output from a test profile collected in Durham, NH.

Depth	u	Pe	Fe	N	T	f	G	P	Qi
m	m/h	bar	N	tr/min	J	Hz	m.s-2	bar	l/min
0.02	9	7	10594	11	3	0.38	17	0.24	25
0.04	152	15	20974	64	26	0.42	18	0.22	25
0.06	138	15	23211	64	34	0.45	20	0.21	25
0.09	138	14	19171	64	45	0.45	19	0.25	24
0.11	147	14	19484	64	40	0.45	20	0.22	24
0.13	150	14	19148	64	32	0.50	20	0.21	23
0.15	137	14	22374	64	32	0.50	19	0.20	24
0.17	130	14	23058	64	33	0.50	18	0.24	24
0.19	135	14	22931	64	37	0.50	19	0.21	24

vi. The MATLAB code included in Appendix B (also provided to the NHDOT before the completion of this research project) can be used to import the raw MWD data in the format presented in Table 3.1 directly.

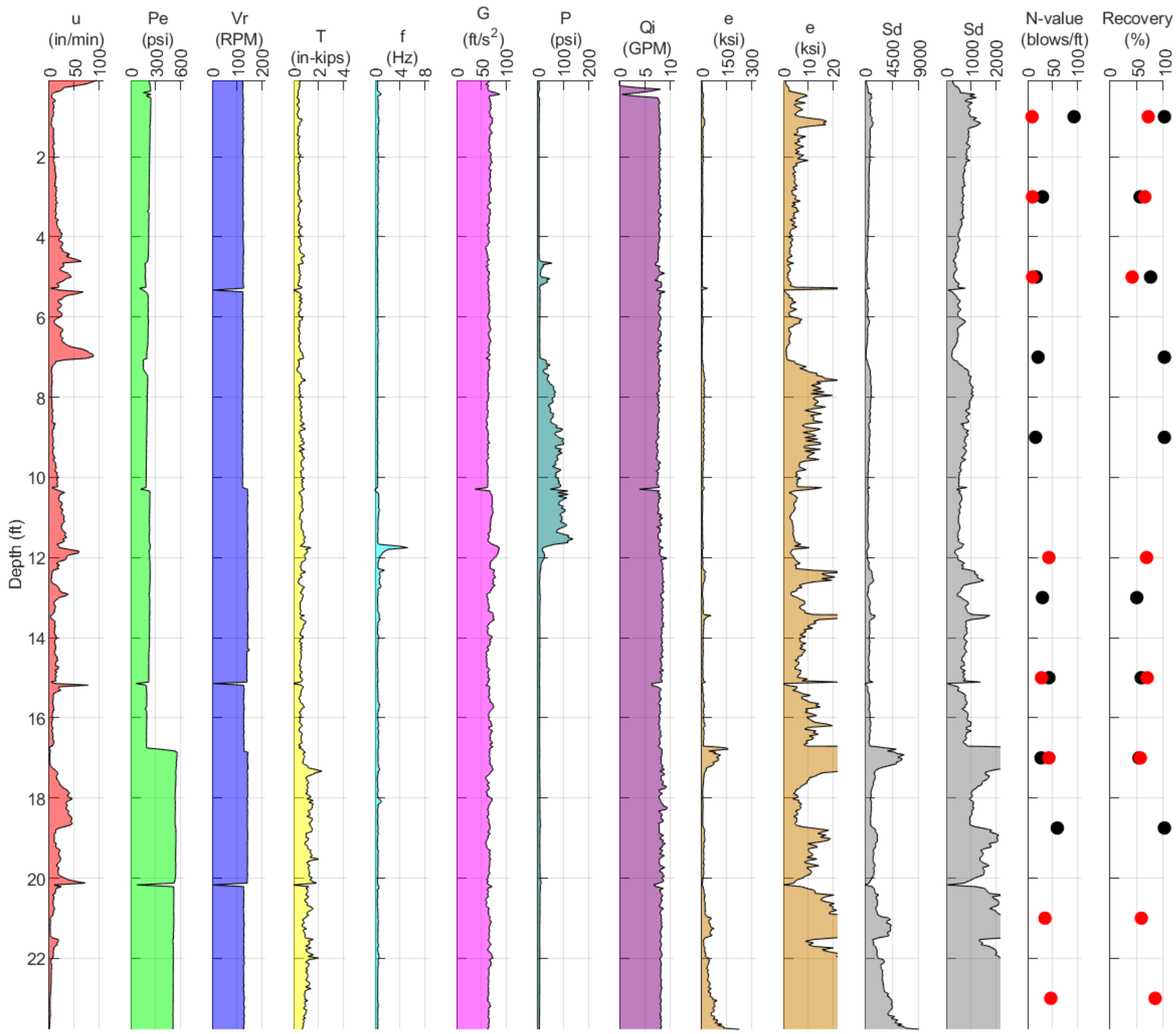
vii. The code automatically corrects the raw data in terms of downthrust pressure, as detailed in this section. In addition, the recorded drilling parameters were used to calculate the compound parameters previously described. If downthrust force (Fe) data is available, the compound parameters will consider the force rather than the downthrust pressure Pe measured with the wired sensor.

viii. If SPT data is available from an adjacent borehole, it can also be imported, following the format presented in Table 3.2 and plotted in the same graph.

Table 3.2. Sample SPT data format from a test profile collected in Durham, NH.

Depth (ft)	**N_{SPT} (blows/ft)**	**Recovery (%)**
1	1	25
3	2	35
5	8	45
7	16	35
9	12	40
11	19	35
13	11	35
15	23	50

ix. The MATLAB code will output a figure with all drilling parameters and the SPT profile, as shown in Figure 3.2.



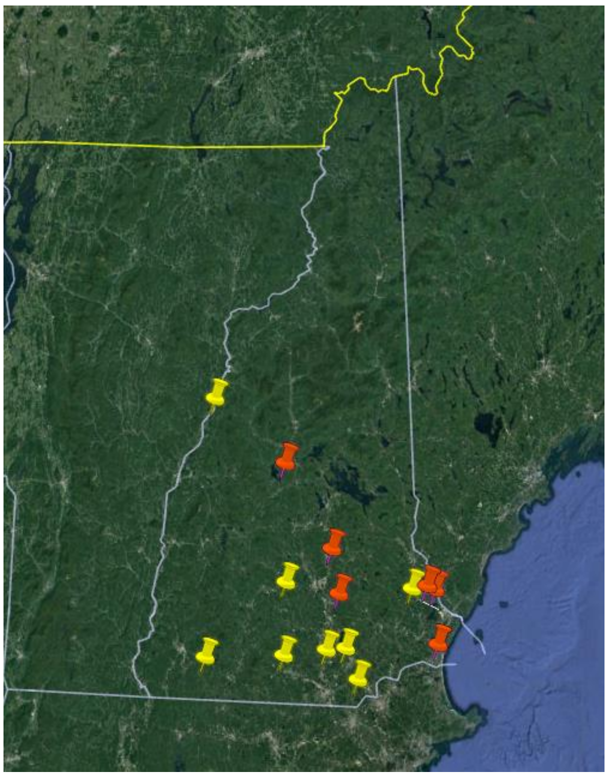
Legend:

u	Penetration rate	P	Mud pressure
Pe	Downthrust pressure	Vr	Rotation rate
Qi	Mud flow	e	Drilling energy
T	Torque	Sd	Somerton Index
f	Frequency	Qt	CPTu corrected tip pressure
G	Acceleration	fs	CPTu corrected sleeve pressure

Figure 3.2. Graphic output generated by the MATLAB code presented in Annex B – test performed in Durham, NH.

4. MWD FIELD EXPERIMENTAL CAMPAIGN

Between July 2021 and August 2024, the NHDOT mobilized the MWD drill rig to 14 sites in New Hampshire, as shown in Figure 4.1. The field experimental campaign performed in this research was divided into two main phases: (1) MWD installation, system improvements, and crew training, and (2) MWD data collection for analysis. The test locations were selected according to the demand of the NHDOT and crew availability. All MWD boreholes were drilled uncased during this test campaign.



Phase 1: **06/21 – 06/2023** MWD system adjustments, evaluation, and crew training	**Phase 2:** **07/2023 – 08/2024** MWD data collection (& number of profiles)
Dover, NH	Bridgewater, NH (2)
Lee, NH	Derry, NH (1)
Merrimack, NH	Durham, NH (4)
Milton, NH	Londonderry, NH (8)
Pelham, NH	Loudon, NH (2)
Troy, NH	Newington, NH (2)
Warner, NH	Seabrook, NH (1)

Figure 4.1. NHDOT MWD testing site locations in New Hampshire.

Since the equipment was initially installed in June 2021, several attempts have been made between UNH and the NHDOT to ensure proper data collection. The adjustments made to the equipment over time, along with the respective timelines, have been detailed in the NHDOT Quarterly reports. The following list summarizes the installations and adjustments performed to the NHDOT drill rig over phase 1 – MWD adjustments and implementation. These adjustments were performed in close communication with Jean Lutz and MWD One.

- MWD system installation.
- Updates to the data logging software for proper data visualization in real-time.
- Significant noise in rotation rate measurements in the first tests required improvement in the rotation collar with studs.
- Calibration of the depth sensor in the field.
- A malfunction in the driller's button compromised the initial data collection by randomly pausing data recording. After different attempts to identify and correct the issue, we opted not to include the driller's button in the MWD setup as it creates an unnecessary step for the driller.
- Installation and attempts to use the TICOR sensor from Jean Lutz to measure torque and downthrust.
- Installation of the Pi Box unit to synchronize with the instrumented drill rod by MWD One.

The first successful torque measurements were performed in Durham, NH, in July 2023 (beginning of phase 2). Since then, 20 MWD profiles (drilling + coring) have been collected along with SPT and CPTu data at six sites. This report highlights the main findings of this experimental campaign and discusses how the recorded data can be interpreted.

4.1. Durham, NH

A total of 4 MWD and 2 SPT profiles were obtained at the Durham test site located on the campus of the University of New Hampshire. The local geology included a combination of artificial fill followed by glacial deposits traditionally encountered in NH (Koteff et al., 1989) over diorite bedrock.

Figure 4.3 presents both SPT profiles obtained at the UNH-Durham site. Comparing both profiles, which are only 24 ft apart, shows the heterogeneity of the subsurface conditions. The presence of erratic boulders along the soil matrix makes it even more complex to delineate an approximate soil profile with representative depths. These stratigraphic features required interrupting the SPT test at different depths to drill through with a roller bit, thus preventing continuous data collection.

In glacial deposits such as those encountered in the Northeast U.S., blow counts are often unreliable since gravel or rock fragments can block the split-spoon, leading to high unreasonable N-values. In many instances, the recovery in SPT sampling was poor, especially in sandy and/or gravelly materials. In addition to requiring drilling through boulders, these limitations increased the duration of a single 23-ft profile to 2 days.

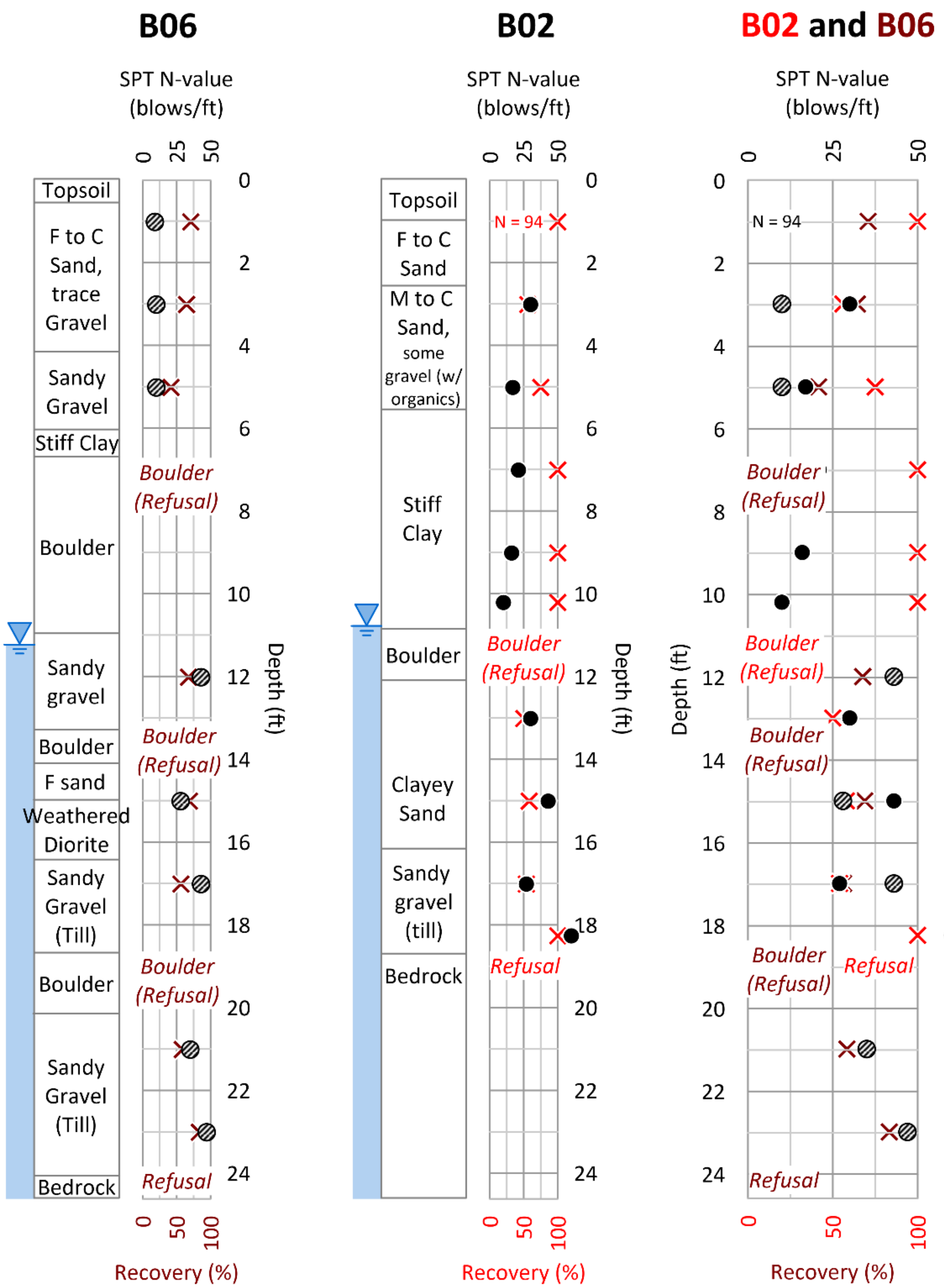


Figure 4.2. Location of test sites in Durham, NH.

Figure 4.3 presents MWD results from borehole B05 in Durham/NH and the SPT results at corresponding depths. The MWD soil profile from 0 to 23 ft was obtained in less than 90 minutes. Some key features can be identified among the data from this test site while drilling through the overburden soils:

- Very low penetration rates are typically associated with harder, more dense materials such as gravels, boulders, cobbles, or bedrock. A sudden decrease (or increase) in advance rate probably suggests a change in stratigraphy for a harder (or softer) material.
- At times, the driller must increase the downthrust to maintain a reasonable penetration rate in harder materials. Increasing the downthrust will lead to an increase in advance rate, but the increase in the drilling rate must be associated with the change in thrust for proper data interpretation.
- Smaller injection water pressures (with no changes in water flow) generally indicate granular materials or fractured zones (in bedrock). In contrast, an increase in water pressure (for the same water flow) indicates more cohesive – less permeable material due to clogging and pressure build-up around the drilling tool caused by the lower permeability of cohesive materials surrounding the drill bit area.
- Spikes in the vibration frequency and oscillations in the vibration acceleration can potentially indicate changes in stratigraphy for harder, highly fractured, or gravelly materials.
- As thrust was increased to drill through harder materials, it was directly reflected in the compound parameters. Changes in compound parameters can be used to identify layer changes and types. The data shows that increased N-values or SPT refusal is usually accompanied by increases in material resistance as reflected by higher Sd and e values.

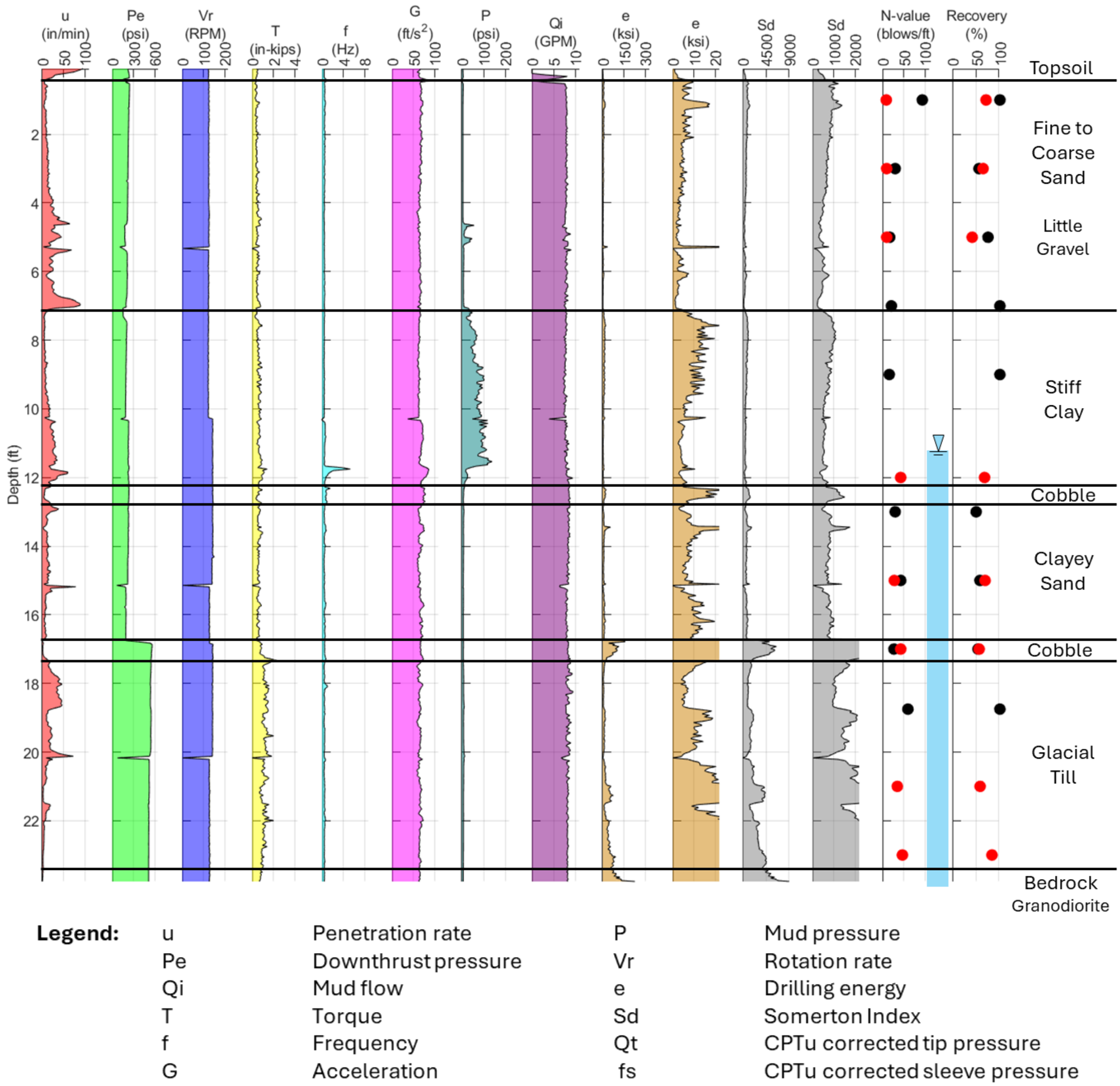


Figure 4.3. MWD profile collected in Durham/NH using a 2.8-in. carbide button roller bit.

In addition to its significant contribution to geotechnical subsurface characterization in soil assessment, continuous MWD monitoring can also help evaluate geological materials that cannot be assessed using conventional SPT or CPTu exploration. These tools cannot be advanced in materials such as boulders, gravelly soils, and bedrock that must be drilled using a roller bit or cored using a core barrel. As shown for the SPT tests performed in Durham/NH, depth intervals where test refusal occurs can lead to a significant lack of data in test profiles that can be potentially used in geotechnical design. In this context, MWD is a complementary tool for assisting in geotechnical investigations, especially along zones of glacial deposits.

For rock, besides laboratory testing of rock cores, the quality of bedrock is mostly evaluated in the field using Rock Quality Designation, or RQD. It is often difficult to distinguish between natural fractures and those induced by drilling or core retrieval, leading to poor estimation of RQD. In cases where the rock is friable or easily fractured during drilling, MWD measurements can allow the driller to make coring adjustments to improve rock cores in terms of quality and recovery, which can lead to improved and more economical foundation design (Sadkowski et al., 2008). Recent research by Rodgers et al. (2021) also highlighted the importance of using operational limits in rock to achieve the best recovery and sample quality in friable and erodible rock formations.

The MWD profile collected in Durham and presented in Figure 4.3 was further evaluated with MWD while coring on bedrock (granodiorite), as shown in Figures 4.4 and 4.5. Figure 4.4 presents the MWD profile for cores 1 and 2, while Figure 4.5 shows the profile corresponding to cores 3 and 4. Coring was performed in this research using a 3.15 in. diameter core bit. The retrieved cores were measured, and RQD was calculated for core runs 1 to 4, as presented in both figures. For a better comparison between the MWD profile and the retrieved cores, selected fractures were highlighted: natural fractures were highlighted in pink, while drilling-induced or fresh natural fractures were highlighted in blue.

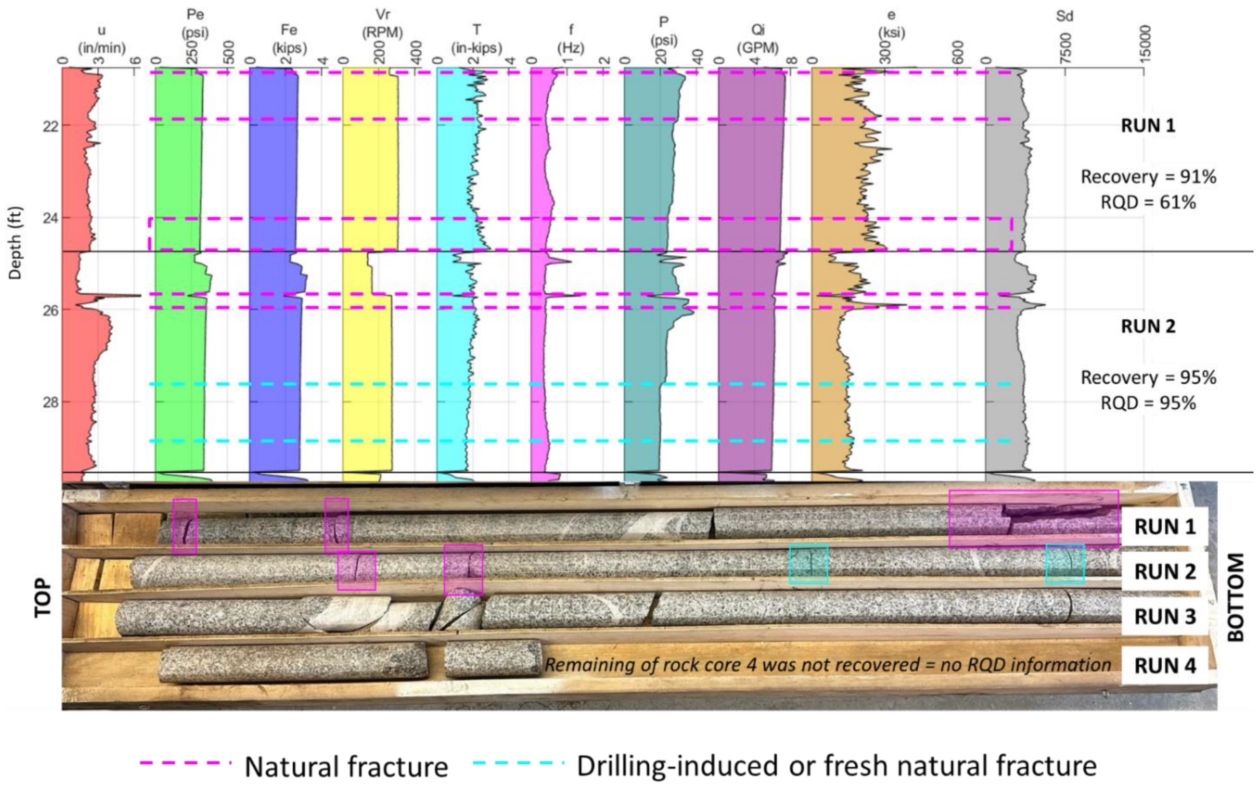


Figure 4.4. MWD profile obtained in Durham/NH while coring using a 3.15 in. diameter core bit.

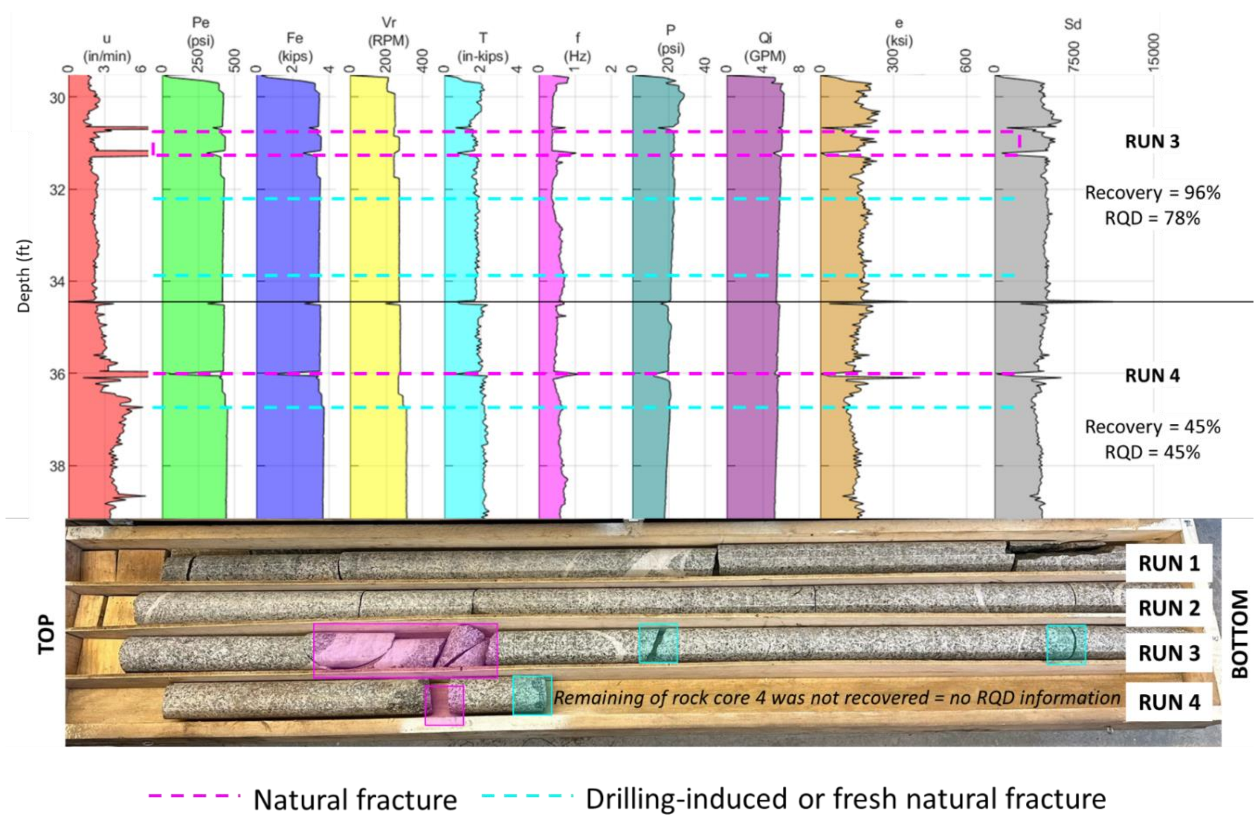


Figure 4.5. MWD profile obtained in Durham/NH while coring using a 3.15 in. diameter core bit.

In bedrock, previous research performed by Sadkowski (2004) and Rodgers et al. (2020) suggested that natural fractures can be detected based on a decrease in water injection pressure, which would not be measured in drilling-induced fractures (Sadkowski, 2004; Rodgers et al., 2020). Such a decrease in pressure while drilling through a natural fracture would be explained by the presence of voids (fractures), which do not occur along intact bedrock cores. It is possible to observe that changes in water pressure were generally measured while drilling through natural fractures, while drilling-induced fractures measured constant water pressures.

Rodgers et al. (2020) also reported that, in core runs with incomplete recovery, the fluid injection pressure could also be used to identify potential natural fractures along missing core sections whose visual analysis is not possible, as occurred for core run 4 in Figure 4.5. Based on an analysis of the injection fluid pressure recorded between 36.7 and 39 ft, the steady plot recorded for this corresponding depth suggests that there were no natural fractures in the section where the core was not retrieved by the core barrel.

4.2. Derry, NH

An additional example of MWD monitoring while coring is presented in Figure 4.6. The figure shows that core run 1 consists of sound to slightly fractured quartzite, while core run 2 consists of moderately weathered schist over quartzite. The significant increases in advance rate suggest that assuming similar bedrock geological materials, the in-place rock is likely fractured or weathered (thus, lower RQD).

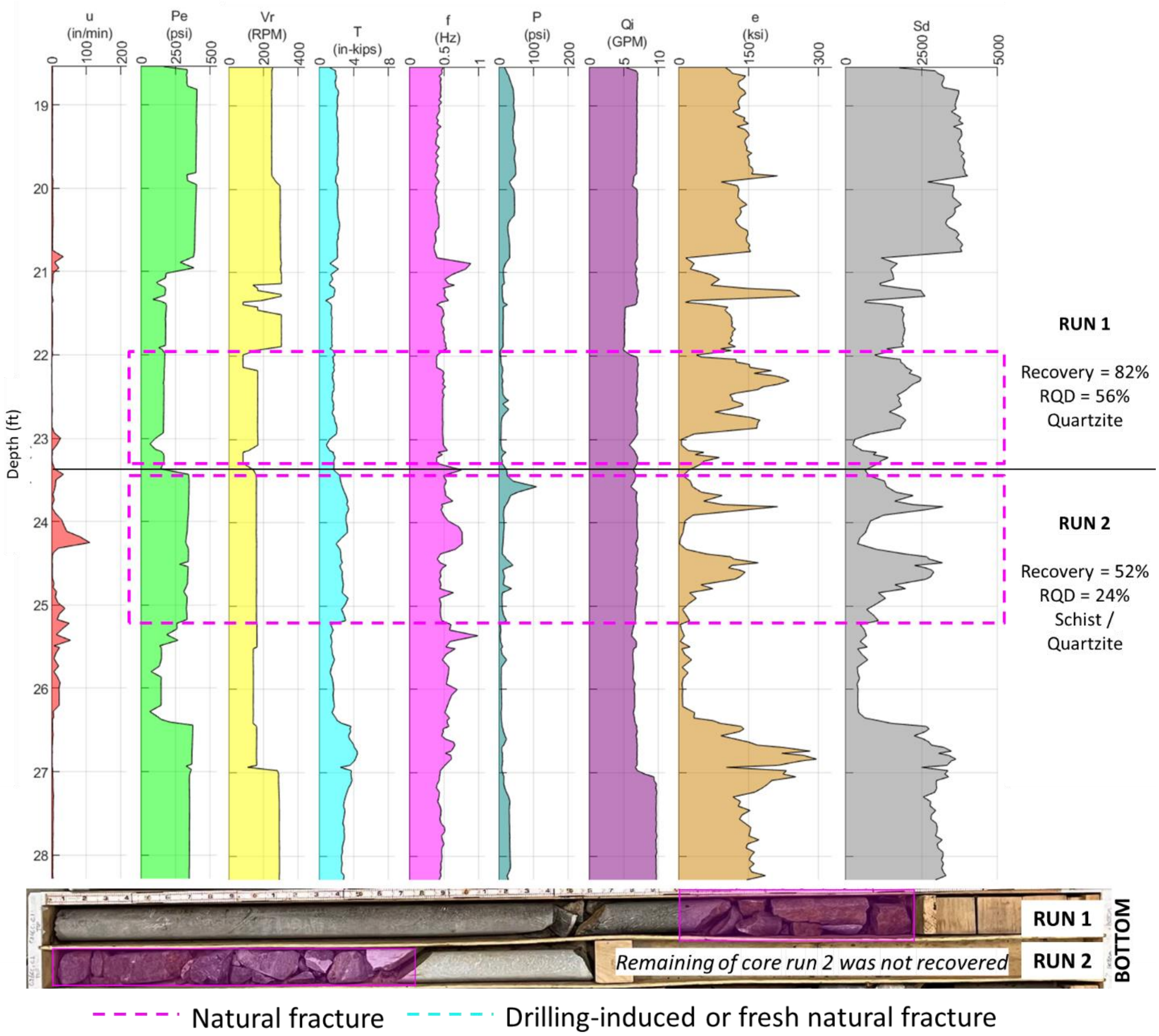
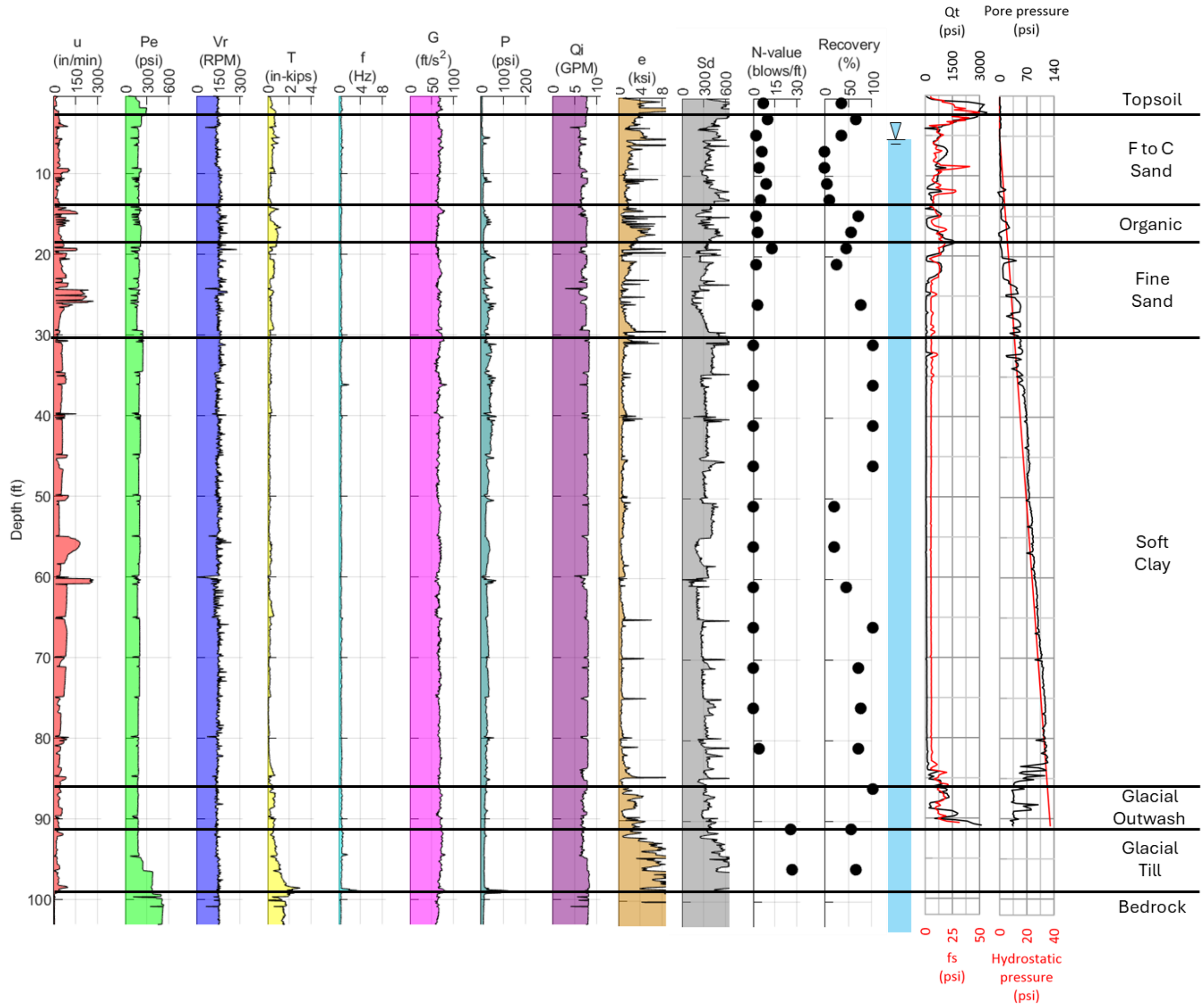


Figure 4.6. MWD profile obtained in Derry/NH while coring using a 3.15 in. diameter core bit.

4.3. Newington, NH

The site is located along the coast of the Piscataqua River, which connects to the Atlantic Ocean. Local geology includes thick layers of marine clay up to 75 ft, followed by glacial till and basalt bedrock. An initial SPT performed by the NHDOT in 2011, about 100 ft from the test boreholes, identified a stratigraphy formed by fill, organic deposits, marine clay, glacial deposits (outwash and till), and bedrock (basalt). A CPTu profile was also performed for this project for comparison with the MWD measurements. Given the significant depth of the boreholes an attempt was made to drill additional boreholes with casing to improve the return flow to the surface. However, fine sand in the subsurface made the casing unthread in all three attempts.

Two MWD profiles up to 100 ft in depth were obtained in Newington alongside profiles of SPT and CPTu soundings. The stratigraphy description in Figure 4.7 was obtained from the SPT samples and corroborated using the CPTu soil identification based on the soil behavior type by Robertson (2010).

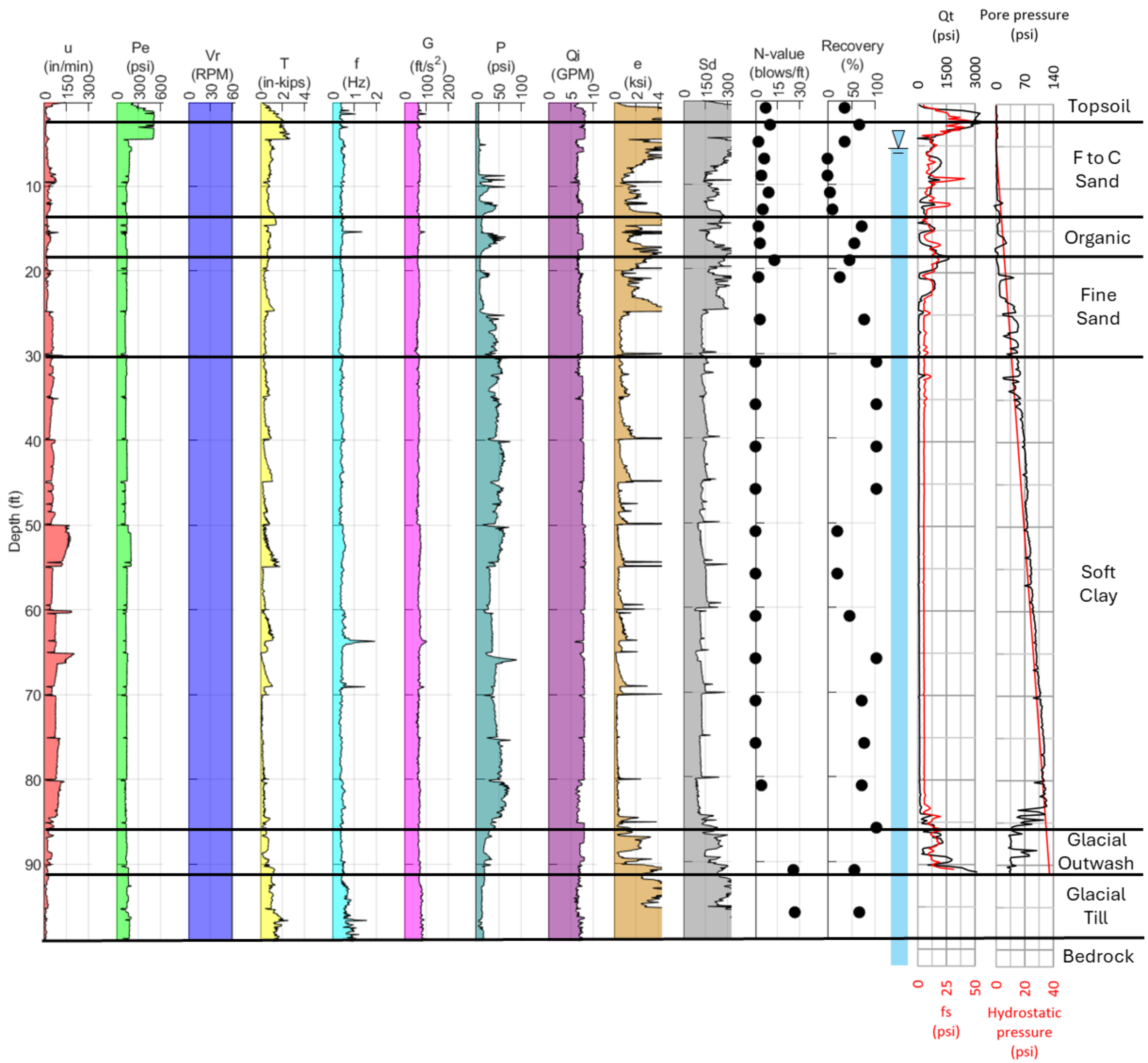


Legend:				
	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure 4.7. MWD B01 profile – Newington, NH.

Due to the low strength of the geological materials, the SPT blow counts did not provide much information on material resistance. From the CPTu profile using a Type 2 piezocone, it is possible to observe how the measured resistance decreases to nearly zero as the probe penetrates the soft, sensitive marine clay layer. The presence of cohesive soil is confirmed by increased penetration porewater pressures. The depth correspondence between changes in ground resistance for both SPT and CPT tests suggests that the local stratigraphy is approximately similar for these two adjacent profiles.

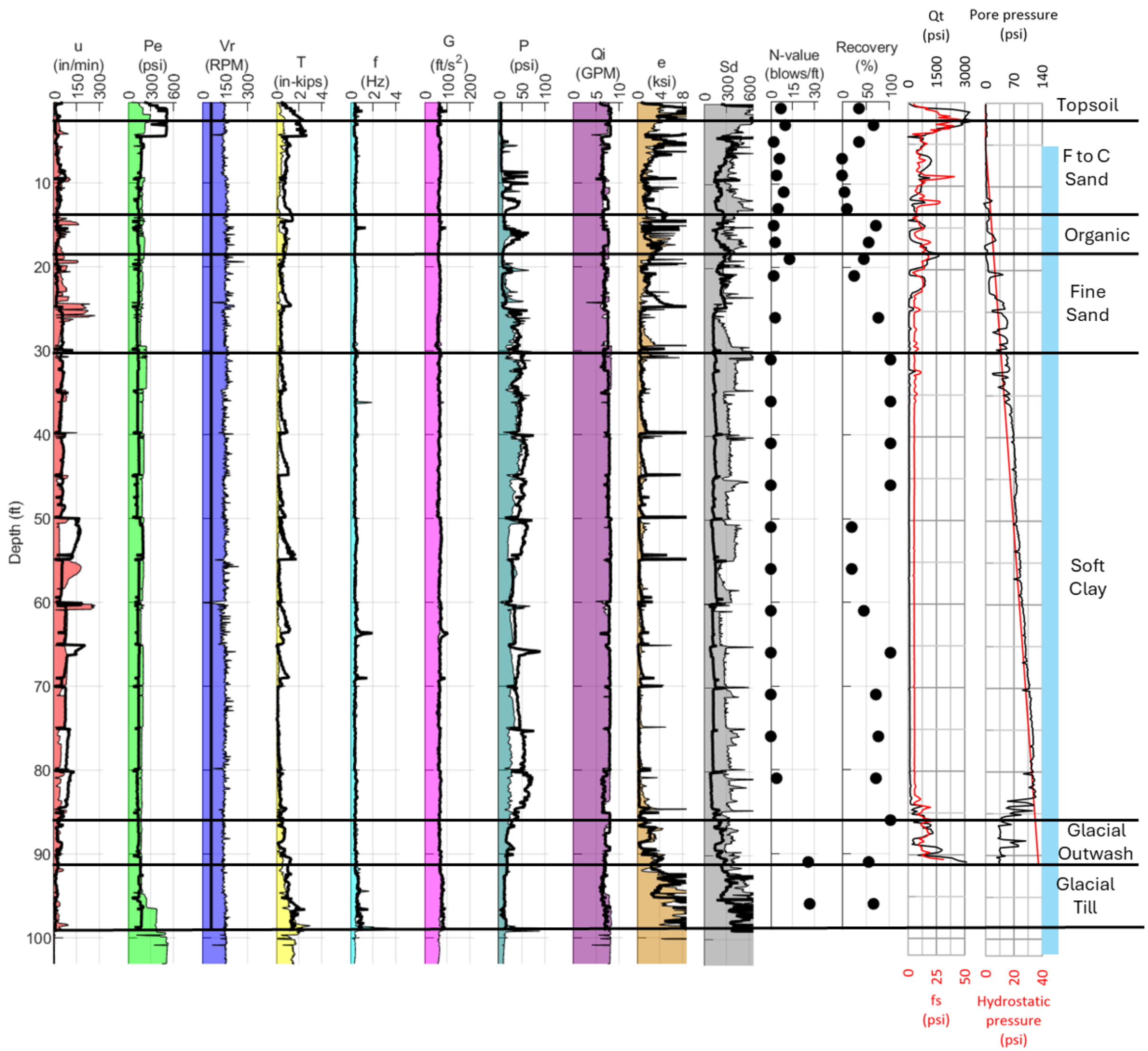
The effect of rotation rate was investigated by decreasing the typical rotation rate used by the NHDOT drill crew from 150 RPM (measured at B01 – Figure 4.7) to 60 RPM in one of the boreholes (B02 – Figure 4.8).



Legend:	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure 4.8. MWD B02 profile – Newington, NH.

Figure 4.9 presents profile B02 (thick black lines) superposed on B01 (color-filled graphs) for a visual comparison.



Legend:	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure 4.9. Superposition of MWD profile B02 on profile B01 – Newington NH.

Different behaviors were observed with the change in rotation, as noted here:

- A lower rotation rate led to higher measured torque while drilling through the clay. Each time a rod was added and drilling was resumed, the torque gradually increased until the next test interruption. This behavior is likely the result of insufficient cutting and plugging of the drill bit, thus increasing the torque necessary to advance the borehole.
- A lower rotation rate led to lower penetration rates in materials that were not clay. The rotation rate did not seem to affect the advance drilling rate in clay; however, the rotation rate is an important parameter to allow the drill bit to cut and evacuate the cuttings to the surface, efficiently without plugging the drill bit.
- Injection water pressure build-up was recorded similarly for both rotation rates but slightly higher for the lower rpm. It is suggested that for these soil conditions, the driller likely used too low water flow, thus allowing for clogging of the drill bit as drilling advanced through the clay layer.

4.4. Londonderry, NH

During MWD drilling operations in Londonderry, the wireless torque sensor was replaced with an updated instrumented rod by MWD One, which measured both torque and downthrust force. The measured force (Fe) was directly compared to the corrected thrust pressure measured with the wired JL sensor (Pe) multiplied by the area of the drill bit, leading to a force value in lbs, as shown in Figure 4.10 for the MWD profile presented in Figure 4.11. This comparison was repeated for all eight experimental trials in Londonderry. It was concluded that the MWD One thrust sensor placed directly at the top of the drill string leads to more accurate and direct thrust measurements than the wired sensor using the hydraulic thrust pressure line. For this reason, all MWD profiles with MWD One thrust measurements used this parameter instead of the JL thrust pressure for the compound parameter calculations. The thrust force was divided by the drill bit area to obtain Pe in psi, as previously shown in Equation 3.1.

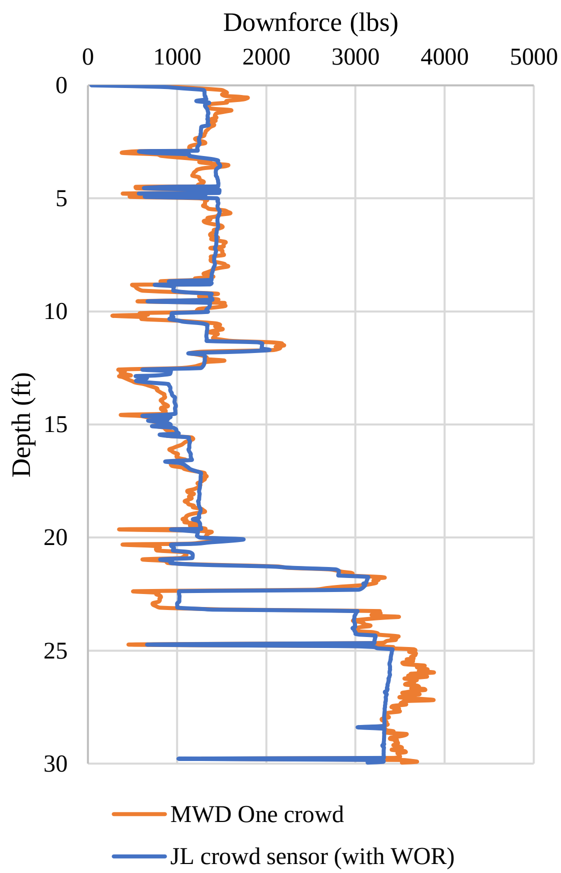


Figure 4.10. Comparison between the downthrust measured with the new MWD One instrumented rod and the thrust pressure measured with the wired Jean Lutz sensor.

The geological materials at the Londonderry site, presented in Figure 4.8, are similar to those from the Durham site. The SPT experienced refusal while testing gravelly soil at a depth of 26 ft. Similar features can be observed on the MWD profile for material identification based on the SPT logs, such as the increase in water pressure indicating a layer of cohesive material, increases in compound parameters for harder materials, and oscillations in the vibration frequency for gravelly material. Given the higher accuracy of the thrust measurements based on the wireless thrust sensor, it can also be inferred that the compound parameters are determined with higher accuracy, which consequently helps identify the stratigraphic layers.

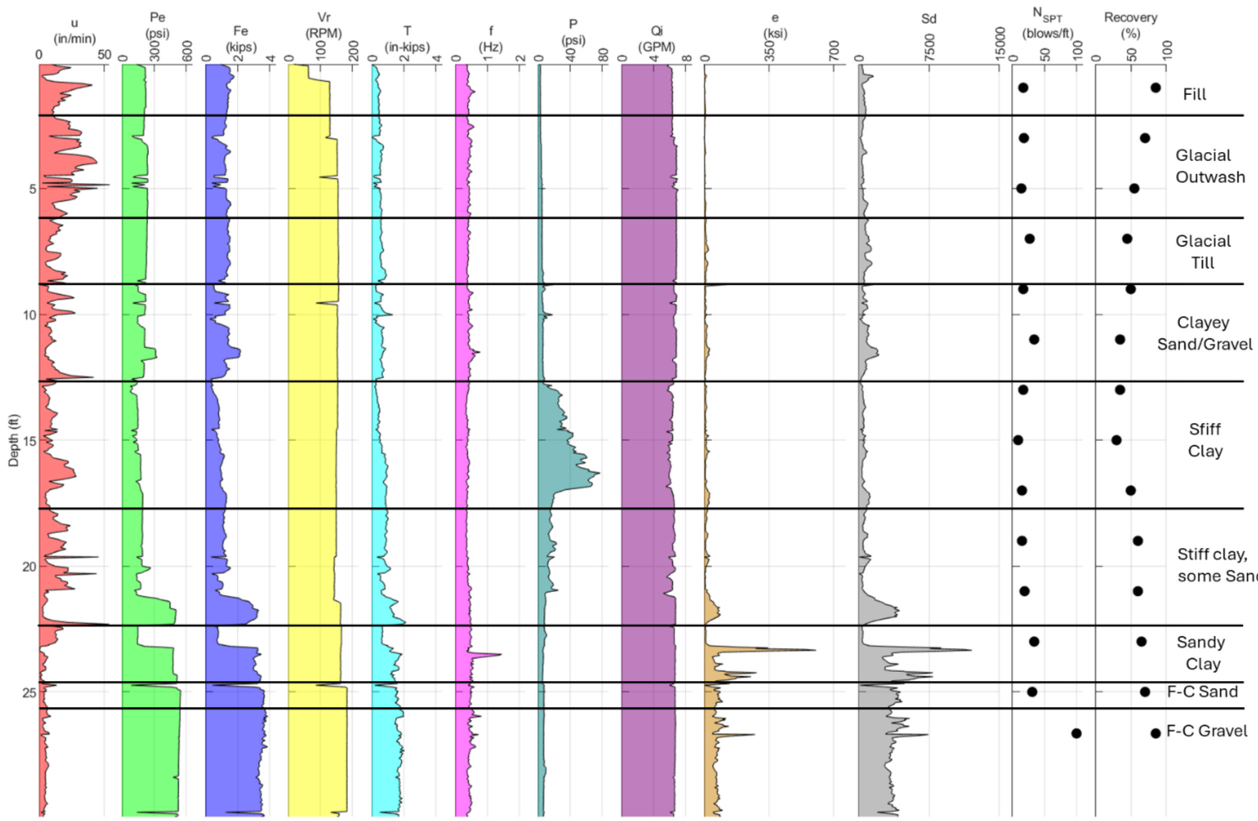


Figure 4.11. MWD borehole B05 – Londonderry NH.

A rock coring profile obtained in bedrock (granite) in Londonderry is presented in Figure 4.12. This profile demonstrates that response drilling parameters (e.g., drilling rate, fluid pressure, torque) depend on drilling parameters imposed by the driller. The high incidence of fractures in Figure 4.12 required the driller to adjust the thrust pressure according to geological conditions, which often demanded a decrease in thrust while drilling through consecutive natural fractures (e.g., 27 and 34 ft). Changes in water pressure and drilling rate can be used to assess bedrock conditions when the parameters imposed by the driller are constant. Otherwise, it is recommended to mainly analyze changes in compound parameters that normalize the effect of drilling conditions.

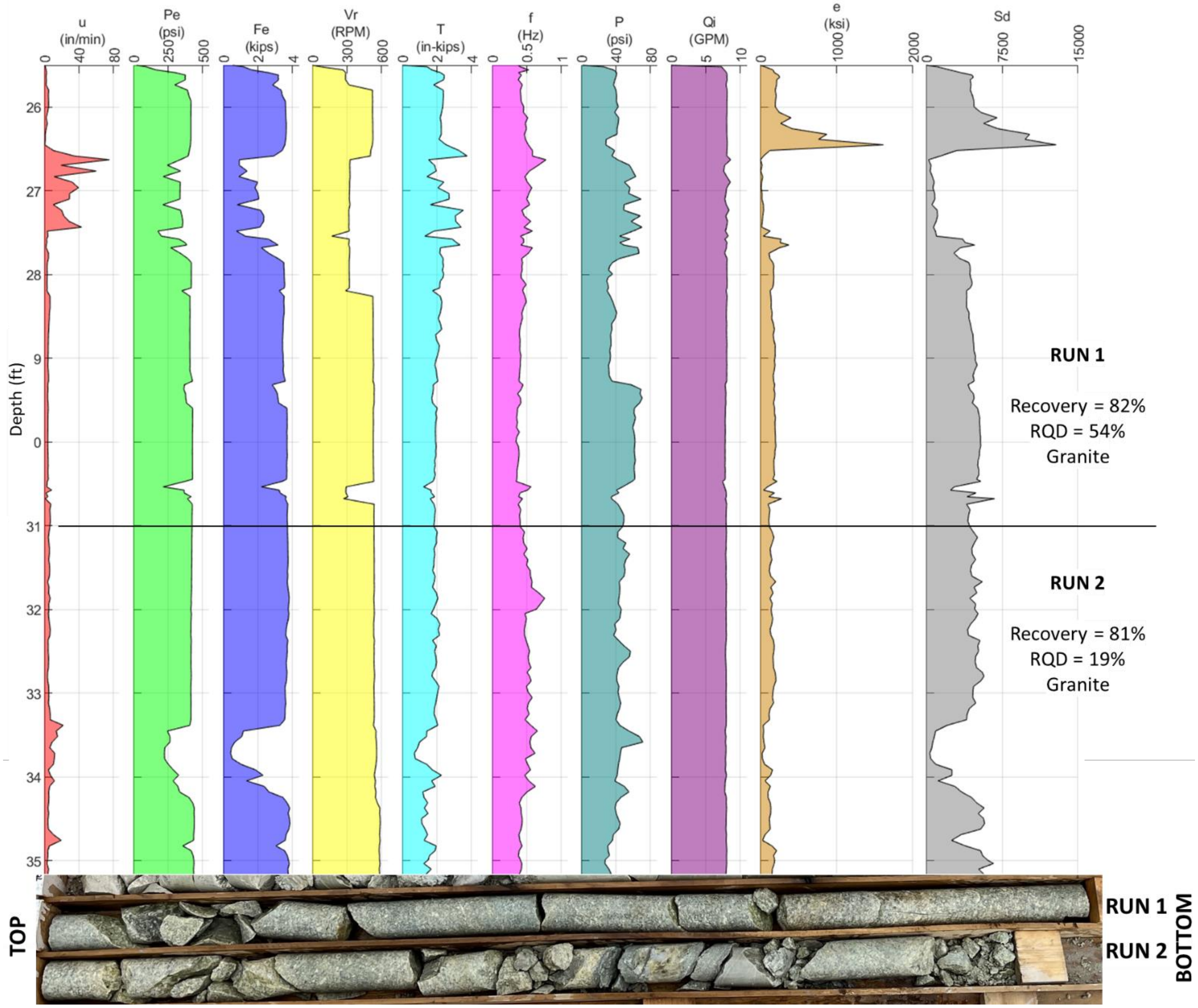


Figure 4.12. MWD coring B01 – Londonderry NH.

For additional MWD profiles obtained while drilling in this research project, the reader is referred to Appendix C – Additional MWD profiles.

5. NHDOT DATABASE OF DRILLING PARAMETERS

A review of the literature previously gathered by Sadkowski (2004) grouped typical penetration rates for different subsurface materials, as shown in Table 5.1. While this information is mostly limited to rock drilling, most data collection was obtained using percussive drilling rather than rotary drilling, which is the conventional practice in the US. However, based on these values, it can be inferred that the penetration rate is an indicator of the resistance to penetration of the drilled medium (Pfister, 1985). This statement is particularly true considering that MWD assessments typically attempt to maintain a constant downthrust, rotation rate, and inflow.

Table 5.1. Typical penetration rates for various subsurface materials (after Sadkowski, 2004).

Material type	Penetration rate (in./min)	Drill rig	Reference
Cavities	> 420	Percussive	Pfister (1985)
Micrite limestones	17 – 21	Percussive	Peck et al. (1987)
Shale	33 – 59	Percussive	Peck et al. (1987)
Gabbro	13 – 21	Percussive	Peck et al. (1987)
Coal	> 49	Blast hole	Scoble et al. (1989)
Competent limestone	> 24	Percussive	Zacas et al. (1995)
Calcareous sandstone	4 – 12	Rotary hydraulic	Garassino and Schinelli (1998)
Gravel	79 – 330	Rotary hydraulic	Gui et al. (2002)

Using all the MWD profiles obtained in the experimental program presented in this report, the average values for all raw and compound drilling parameters were extracted from each soil layer of known stratigraphy. The data were grouped by material type, regardless of site location, into six main categories: clay, sand, glacial outwash, glacial till, gravel, and rock. All data presented in Table 5.2 refers to only data obtained while drilling with the 2.8-in. diameter carbide button roller bit. The reference values presented in this report should be expanded as additional data is collected by the NHDOT to provide a larger database that could ultimately help identify geological materials more efficiently, reducing the need for continuous SPT sampling and in fewer boreholes.

Table 5.2 presents the minimum and maximum average values obtained along layers of a given material type (sand, clay, gravel, glacial outwash, glacial till, bedrock), grouping data from all boreholes obtained in this research. Ranges of measurements for each drilling parameter, as listed in the table, are defined based on the minimum and maximum averages for each material type.

Observations regarding the different data ranges for each drilling parameter were annotated in red or green in Table 5.2. It can be observed that the drilling fluid pressure has a high potential to differentiate between cohesive and non-cohesive materials based on measured ranges only. However, the other drilling parameters typically present similar or intersecting measuring ranges for geological materials of significantly different characteristics (e.g., sand and bedrock). Therefore, at this moment, the geological profiling based on MWD measurements still requires additional SPT or CPTu testing at adjacent boreholes to evaluate ground conditions based on standardized methods used in current geotechnical practice.

Table 5.2. Database of raw and compound drilling parameters from this research project.

Variable	Field description	Minimum average	Maximum average
Acceleration (ft/s²) ***Similar ranges for all materials***	Clay	61	67
	Sand	61	83
	Gravel	63	72
	Glacial outwash	63	70
	Glacial till	65	80
	Rock	64	74
Drillability strength ***Increases when the material deformability decreases***	Clay	0.0003	0.0187
	Sand	0.0002	0.0095
	Gravel	0.0003	0.1238
	Glacial outwash	0.0021	0.0161
	Glacial till	0.0111	0.0776
	Rock	0.0289	0.0845
Drilling energy (ksi) ***Not ideal for general material descriptions***	Clay	0.7	10.3
	Sand	0.5	10.3
	Gravel	0.6	96.7
	Glacial outwash	2.1	6.7
	Glacial till	9.5	52.2
	Rock	17.6	110.8
Frequency (Hz) ***Similar ranges for all materials***	Clay	0.38	0.47
	Sand	0.39	1.11
	Gravel	0.48	0.85
	Glacial outwash	0.42	0.53
	Glacial till	0.45	0.83
	Rock	0.45	0.90
Downthrust force (kips) ***Parameter controlled by the driller***	Clay	0.6	1.5
	Sand	1.0	1.9
	Gravel	1.1	3.7
	Glacial outwash	1.0	1.6
	Glacial till	1.6	3.4
	Rock	0.9	3.7
Water flow (GPM) ***Parameter controlled by the driller***	Clay	6	10
	Sand	5	10
	Gravel	6	9
	Glacial outwash	0	10
	Glacial till	7	10
	Rock	6	10
Water pressure (psi) ***Possibly a good indicator of cohesive soil***	Clay	26	78
	Sand	1	22
	Gravel	6	8
	Glacial outwash	8	23
	Glacial till	8	15
	Rock	2	45

Table 5.2 (cont.). Database of raw and compound drilling parameters from this research project.

Variable	**Field description**	**Minimum average**	**Maximum average**
Corrected thrust pressure (psi) *Parameter controlled by the driller*	Clay	75	199
	Sand	173	289
	Gravel	185	539
	Glacial outwash	143	282
	Glacial till	167	521
	Rock	141	538
Soil-rock resistance *Not ideal for general material descriptions*	Clay	3	21
	Sand	1	33
	Gravel	5	188
	Glacial outwash	5	14
	Glacial till	15	104
	Rock	53	438
Somerton Index *Similar ranges for most materials*	Clay	186	723
	Sand	194	1217
	Gravel	215	4518
	Glacial outwash	346	693
	Glacial till	743	2982
	Rock	710	6487
Torque (k-in) *Similar ranges for most materials*	Clay	0.1	0.7
	Sand	0.3	1.0
	Gravel	0.3	1.6
	Glacial outwash	0.5	1.0
	Glacial till	0.9	1.9
	Rock	0.4	1.7
Advance rate (in/min) *Not ideal for general material descriptions*	Clay	7	73
	Sand	8	202
	Gravel	4	56
	Glacial outwash	25	38
	Glacial till	8	25
	Rock	1	11
Rotation rate (RPM) *Parameter controlled by the driller*	Clay	60	152
	Sand	47	176
	Gravel	60	184
	Glacial outwash	60	152
	Glacial till	60	160
	Rock	68	186
Water pressure/ Thrust pressure *Possibly a good indicator of cohesive soil*	Clay	0.15	0.52
	Sand	0.10	0.23
	Gravel	0.05	0.17
	Glacial outwash	0.00	0.20
	Glacial till	0.07	0.17
	Rock	0.05	0.27

6. PORTABLE MEASUREMENT WHILE DRILLING DEVICE

Despite the versatility of MWD equipment and its rising interest in the geotechnical community, this in situ test requires the mobilization of large equipment and specialized drilling crew. In areas where accessibility is an issue and/or only shallow subsurface investigation is necessary, a portable MWD (PMWD) can be used instead of a conventional drill rig. Such portable MWD equipment was designed and built by the Center for Studies on Risks, the Environment, Mobility and Urban Planning (CEREMA) in France. The PMWD, shown in Figure 7.1, consists of sensors mounted on a cordless rotary drill that records time, depth, downforce, rotation, and torque. The system communicates wirelessly with a USB antenna installed on any computer, usually within 30 feet of the equipment. The cordless drill has two handles facilitating the drilling process, especially on hard ground.

Figure 7.1. Portable MWD equipment. (a) Constituting parts, (b) frontal view, and (c) field test in Enfield, NH.

The portable MWD equipment provides four main parameters as a function of depth (the symbols for the drilling parameters have been modified to avoid confusion between measurements performed with the conventional MWD and the PMWD). In addition, since the system was developed in Europe, the equipment software reads and exports data in SI units. A lightweight dynamic cone penetrometer (LDCP) validated results under laboratory and field conditions.

- Advance rate, or penetration rate (V_A), in m/s
- Rotation rate (V_R), in rotations per minute (rpm)
- Downforce (F_{down}), in N
- Torque (T), in N.m

This research project introduced the portable MWD equipment as an innovative and lightweight tool for rapidly assessing shallow subsurface in laboratory and field rockfall experiments. PMWD measurements were initially obtained to assess the heterogeneity of ground surfaces encountered in rockfall-prone areas, but they can be used in future NHDOT projects where large equipment mobilization may not be possible or necessary.

Each PMWD test provided a ground profile formed by parameters recorded individually by each sensor (i.e., drilling rate, rotation rate, down pressure, torque) and previously described compound parameters. Two typical profiles on sand and sandy gravel are shown in Figure 7.2. The LDCP provides resistance to penetration results as a function of depth. The raw data is supplied in irregular depth intervals, according to the vertical displacement of the penetrometer per blow. Figure 7.2 presents two typical LDCP profiles obtained on sand and sandy gravel prepared under controlled conditions. Equations 8.1 to 8.5 present the same compound parameters previously introduced in section 4 for the conventional MWD but include the corresponding SI units used for the PMWD.

$$P_E = F_{down}/A_{drill\ bit} \tag{8.1}$$

Where: P_E = downthrust pressure (MPa)

F_{down} = downthrust force (MN)

$A_{drill\ bit}$ = drill bit area (m²)

$$S_D = P_E * (V_R/V_A)^{0.5} \tag{8.2}$$

Where: S_D = Somerton Index (unitless)

P_E = downthrust pressure (MPa)

V_R = rotation rate (rpm)

V_A = advance rate (m/s)

$$E_S = P_E + (2 * \pi * V_R * T)/(A * V_A) \tag{8.3}$$

$$E_R = (2 * \pi * V_R * T)/(A * V_A) \tag{8.4}$$

Where: E_S = specific drilling energy (MJ/m³)

E_R = drilling energy by rotation torque (MJ/m³)

P_E = down thrust pressure (MPa)

V_R = rotation rate (rpm)

T = torque (MN.m)

A = drill bit area (m²)

V_A = advance rate (m/s)

$$P_R = (time)_{Z\,=\,0.025\,m} \tag{8.5}$$

Where P_R = penetration resistance (s)

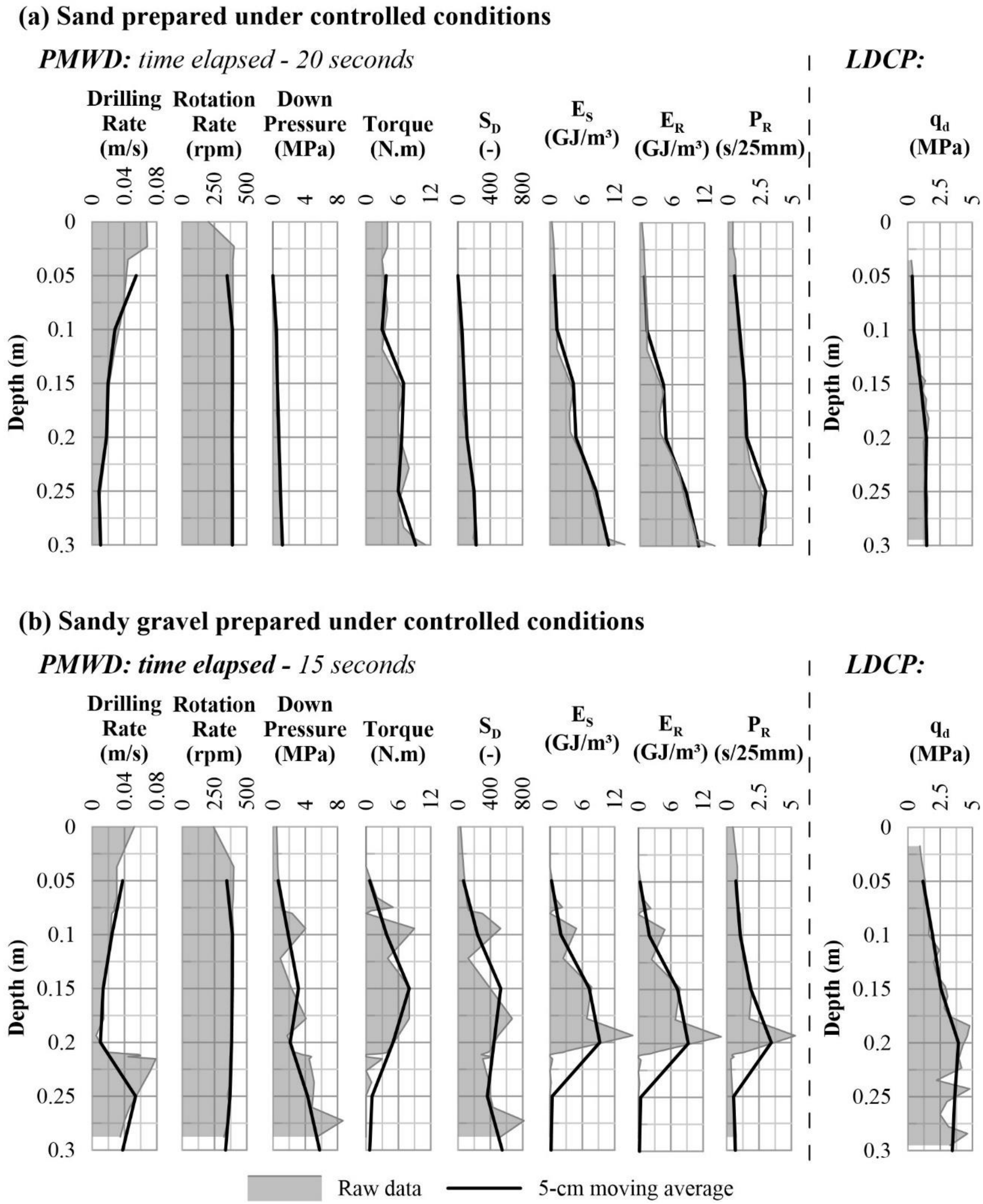


Figure 7.2. Examples of PMWD and LDCP profiles obtained under controlled conditions on sand and sandy gravel.

The high variability due to the presence of pebbles required the use of moving averages for a more objective assessment of subsurface conditions. The hatched gray areas represent the raw data, measured at irregular depth intervals according to the time step (PMWD) or increments per blow (LDCP). The black lines represent a 5-cm moving average of each plot. It is possible to observe that, while the sand plots show little to no variability, the sandy gravel has a significant variability in measured drilling parameters and dynamic tip resistance (q_d), attributed mostly to pebbles randomly distributed in the ground. The parameter changes at approximately 0.20 m illustrate the end of the first compaction layer.

The rotation rate (V_R) was constant at 380 rpm for both materials. In general, higher drilling rates (V_A) indicate softer materials for a constant rotation and applied down pressure, while lower rates suggest the presence of harder ground. However, the V_A parameter cannot be assessed objectively as the operator needs to apply variable pressures to drill through materials. While a regular increase in P_E is observed on sand, variable pressures were recorded while drilling on sandy gravel to advance through the pebbles in the ground. Variations in measured torque also accompanied these variations in downforce.

As the bottom layer approaches, ground resistance increases with increasing Somerton Index (S_D) and drilling energy (E_S). The increase in resistance is also seen in the penetrometer profiles, where the sand presented a maximum q_d of 1.3 MPa, and the sandy gravel recorded an average maximum value of 3.8 MPa. A similar increasing trend is observed in both materials for the Somerton Index, where a maximum value of 200 was obtained for sand, and a maximum average of 600 was recorded on sandy gravel.

While correlations between the penetrometer tip resistance and PMWD results were attempted for all parameters shown in Figure 7.2, this report presents select relationships established for both materials, as shown in Figure 7.3. The 5 cm moving average from each profile was summed at each depth increment and divided by the number of tests. In the upper left plot, it was observed that the calculated S_D data from drilling parameters presents an approximately linear relationship for granular materials under controlled conditions despite the heterogeneity observed in the sandy gravel. Although changes in down pressure were recorded in all tests, it is still possible to observe a relationship between the penetration resistance (P_R, directly related to V_A) and q_d for the sand, a relatively uniform material. This association is not observed for heterogeneous ground conditions, which is often expected in the field. In addition, a linear relationship between the tip resistance and the drilling energies (E_S and E_R, neglecting the thrust pressure) is also observed for the sand, as shown in the plots on the right of Figure 7.3.

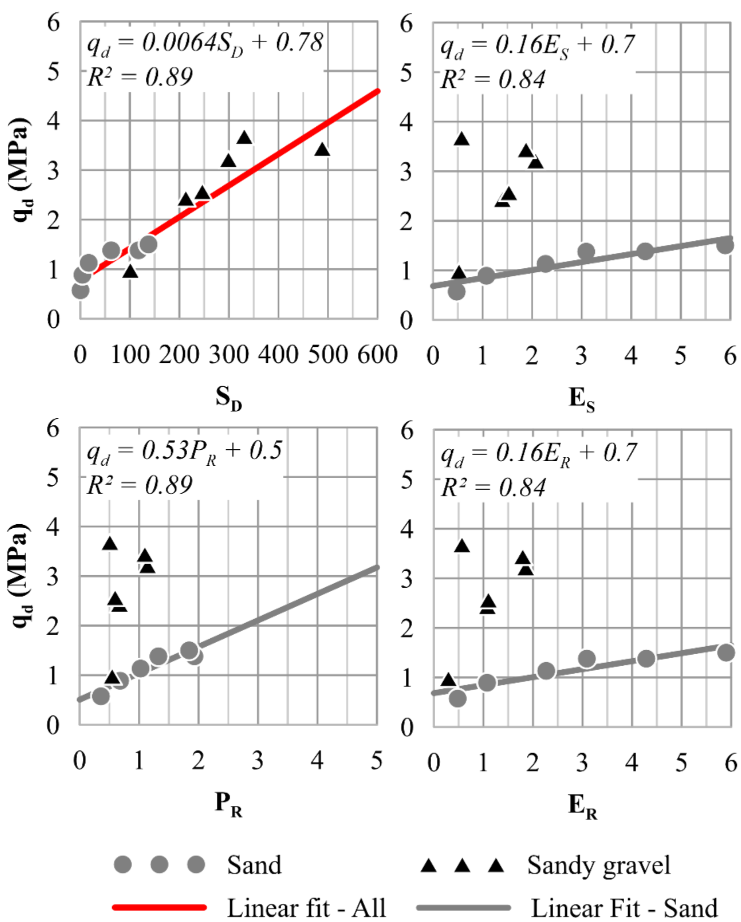


Figure 7.3. Relationship between the calculated PMWD compound parameters and penetrometer tip resistance.

PMWD and LDCP results under controlled conditions allowed to determine ranges of measurements for q_d and S_D that can be used to differentiate the ground materials between two categories for ground mapping in rockfall-prone areas across NHDOT sites: soft and medium ground. These ranges, shown in Figure 7.4, were used in practice to characterize test slopes based on an interest depth of 0.1 m.

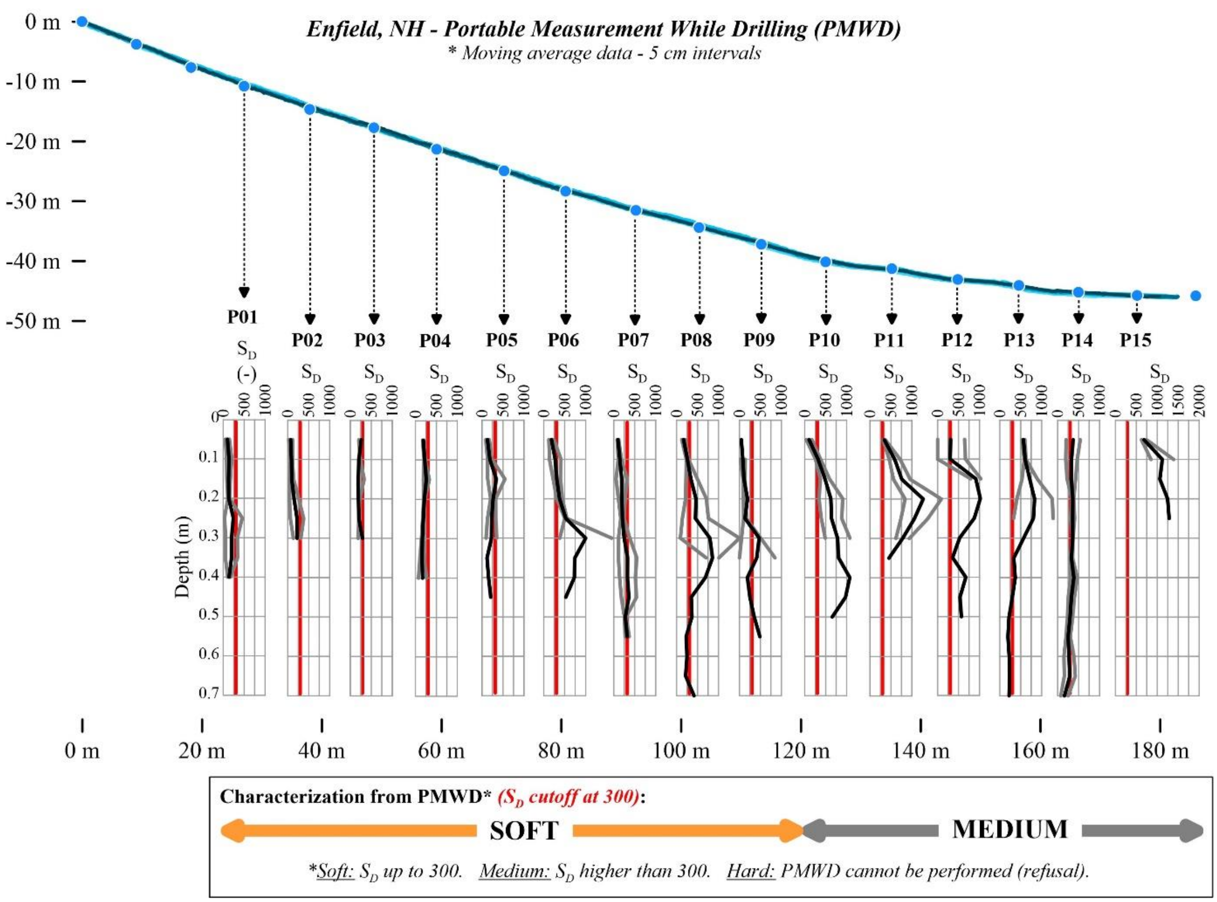


Figure 7.4. Distribution and results of PMWD tests at a rockfall test slope in NH, averages and standard deviations.

Figure 7.4 presents the average Somerton Index (S_D) values obtained along the test slope with the portable MWD. While each average profile was calculated from approximately 5 LDCP tests, the average PMWD profile was determined based on 2 to 3 tests at each elevation. S_D values over depth are uniform and present values below 300 between P01 and P05. As the tests under controlled conditions demonstrated, the medium soil recorded values of approximately 300 at the depth of interest. Therefore, based on results from both test campaigns, it is estimated that the upper slope is mostly constituted by a softer soil of lower resistance, while the lower slope starting at P10 is mostly formed by a medium, heterogeneous soil with erratic pebbles or cobbles.

Based on these experiments, the PMWD is a portable geotechnical tool that can obtain drilling parameter measurements at sites that are not easily accessible with conventional drill rigs. In addition, this technique allows the rapid assessment of subsurface conditions at shallow depths without mobilizing heavy equipment.

The PMWD results were directly compared to LDCP profiles, and measurements from both methods were observed to be comparable and equivalent. Under controlled conditions, a linear response was found between the LDCP resistance and the Somerton Index from the PMWD. This observation concludes that a lightweight dynamic cone penetrometer might be sufficient to perform ground assessments at shallow depths when only resistance to penetration or a rough material description are needed for geotechnical design. This technique would be recommended to the NHDOT at shallow depth interests and potential rockfall sites due to its lightweight equipment and the reduced number of measured variables (depth and qd), simplifying data reduction and analysis.

While the PMWD currently consists of a prototype, improvements in the equipment weight and user software/antenna reach can potentially make it more competitive in the geotechnical market since it provides a large number of drilling parameters that can be combined differently to assess subsurface conditions. In addition to the concurrent development of MWD standards and analysis techniques in the United States, this equipment presents a significant potential for research development as it may allow more precise characterization of geotechnical features at shallow depths.

7. COLLABORATION WITH MWD USERS

- MWD Users Group

The MWD user group was established in 2021 in cooperation with the FHWA and DFI to share information and provide a forum for interaction among current and prospective MWD users across the country and worldwide.

Since October 2021, online meetings have been held on the third Wednesday of each month. These meetings have allowed participants to exchange experiences, analysis approaches, testing equipment, innovations, and testing standards. The MWD user group is currently hosted by DFI and can be accessed by visiting the following link: dfi.org/mwd. In addition, several presentations have been made to various groups including the following:

- Presentations of workshops to MWD users and prospect users
    - Deep Foundations Institute, January 2021
    - DFI IT$ Money, April 2021
    - Association of Drilled Shafts Contractors Summer meeting, July 2022
    - Transportation Research Board Conference, January 2023
    - Kansas City Geotechnical Conference, April 2023
    - Northeast States Geotechnical Engineering Conference, October 2023
    - International Foundations Congress and Equipment Expo, May 2024
    - International Conference on Geotechnical and Geophysical Site Characterization, June 2024

8. SUMMARY, CONCLUSIONS AND PERSPECTIVES

8.1. Summary

This research aimed to implement and integrate Measurement While Drilling into subsurface investigation practices as an additional evaluation tool for the New Hampshire Department of Transportation. In order to achieve this objective, this research:

- Installed a newly purchased MWD system on one of the NHDOT rigs.
- Purchased and installed a wireless torque sensor to be fitted to the mechanically driven rig operated by the NHDOT.
- Performed MWD boreholes in parallel with SPT tests and rock coring.
- Evaluated the MWD data obtained with conventional geotechnical tests.
- Collaborated with other MWD users and prospect users across the U.S. and worldwide.

The measurement while drilling equipment, consisting of several wired sensors and a wireless torque/thrust sensor, was installed on the NHDOT and verified during an initial experimental campaign performed in six sites in New Hampshire. After the equipment was successfully installed and ready for use, a user manual (included in Annex A) was written for reference in future data collection.

After the initial equipment installation, verification, and personnel training stage, MWD data was collected and analyzed from seven NHDOT sites. The collected data encompassed various geological layers, from thick layers of sensitive clay to heterogeneous glacial deposits with erratic boulders, in addition to bedrock. The MWD data was collected in complement with conventional, standardized geotechnical testing (e.g., SPT, CPTu) performed at adjacent boreholes. This report introduced the latest MWD equipment and presented detailed and new information on data reduction, processing, and analysis.

A newly acquired CME 55 drill rig was delivered to the NHDOT in July 2024. Once accepted by the DOT, we have been working with the drill crew to troubleshoot the new MWD system installed on this new drill rig.

In addition to the conventional MWD system described in this report, this research has also evaluated a portable Measurement While Drilling (PMWD) device for shallow subsurface investigation. This equipment was directly compared to a standardized lightweight dynamic cone penetrometer, used to assess ground conditions at rockfall-prone slope locations inaccessible to conventional drill rigs.

8.2. Conclusions

The following conclusions can be made or confirmed with this research:

The latest Measurement While Drilling equipment was successfully installed on one of the NHDOT drill rigs.

- The installed MWD equipment consisted of wired (depth, rotation, thrust pressure, water pressure, water flow, vibration) and wireless (torque, thrust force) sensors that communicate with a junction box and data logger. The equipment is now fully functional, and the data collection procedure is user-friendly. Data files can be easily exported to a USB drive.
- The continuous subsurface characterization provided by the MWD system did not interfere with drilling operations. Data collection was successfully and independently performed by NHDOT personnel using the user manual written in this research project.
- Different drillers successfully used the equipment for the full duration of this experimental campaign, highlighting that specialized training is not necessary to use the MWD

equipment. The real-time monitoring of drilling parameters could help the driller understand geological conditions and adjust their drilling techniques accordingly.

- The short duration to drill a full MWD borehole was presented as an advantage over conventional SPT testing to drillers and engineers since the early stages of this research project.

A complete assessment of drilling and compound parameters must include torque measurements collected at the top of the drill string in mechanically driven rigs.

- Torque measurements are required to better understand the ground response to drilling and calculate energy-related compound parameters. Without torque measurements, users are mostly limited to an assessment of subsurface conditions based on the Somerton Index, a "unitless" parameter calculated differently between the upcoming US standards and the current European standards. Therefore, torque measurements are required for a more objective site-to-site comparison of geological profiling between different research groups.
- Measuring torque in mechanically driven rigs is a challenging task. It requires a wireless device that is connected directly at the top of the drill string and communicates wirelessly with the data logger. This research evaluated two newly developed torque sensors, but only one (MWD One) could successfully collect data at our test sites.
- The wireless torque device by MWD One communicates easily with the existing MWD setup and enhances the measured data quality by including a thrust force sensor. The thrust force measurements were directly compared to all thrust pressure measurements at each borehole, and it was verified that thrust measurements at the top of the drill string provide more accurate and precise data compared to the wired sensor installed along the hydraulic thrust line.

MWD profiles were successfully collected at sites of different geology and compared to standard geotechnical testing (SPT and CPTu).

- The continuous subsurface characterization provided by the MWD system could help evaluate geological materials that could not be otherwise assessed during conventional SPT or CPTu exploration. These tools cannot be advanced in materials such as boulders, gravelly soils, and bedrock that must be drilled through with a roller bit.
- In glacial deposits such as those encountered in the northeast U.S., blow counts were often unreliable when split-barrel samples were blocked by gravel or rock fragments, leading to high unreasonable N-values. In this context, obtaining MWD profiles on soils of similar characteristics provided more precise information on subsurface conditions without relying only on blow counts and limited sample recovery.

Some key features could be identified among the MWD data while drilling on soil overburden and rock coring, which is displayed on the data logger screen in real-time while drilling, to assess ground conditions:

- Very low penetration rates are typically associated with harder, more dense materials such as gravels, boulders, cobbles, or bedrock. A sudden decrease (or increase) in advance rate probably suggests a change in stratigraphy for a harder (or softer) material. While coring in bedrock, a sudden increase in the drilling rate may also suggest a highly fractured/weathered zone.
- At times, the driller must increase the downthrust to maintain a reasonable penetration rate in harder materials. Increasing the downthrust will lead to an increase in advance rate, but the increase in the drilling rate must be associated with the change in thrust for proper data interpretation.

- Smaller injection water pressures (with no changes in water flow) generally indicate granular materials or fractured zones (in bedrock). In contrast, an increase in water pressure (for the same water flow) indicates more cohesive – less permeable material due to clogging and pressure build-up around the drilling tool caused by the lower permeability of cohesive materials. While coring on bedrock, a decrease in injection pressure can be associated with natural fractures or voids at a given drilled depth.
- Spikes in the vibration frequency and oscillations in the vibration acceleration can potentially indicate changes in stratigraphy for harder, highly fractured or gravelly materials.
- As thrust was increased to drill through harder materials, it was directly reflected in the compound parameters. Changes in compound parameters can be used to identify layer types. The data shows that increased N-values or SPT refusal are usually accompanied by increases in material resistance as reflected by higher Somerton Index and drilling energy values.
- While drilling in thick, soft clay layers, decreasing the rotation rate led to higher measured torque while drilling through the clay. Each time a rod was added and drilling was resumed, the torque gradually increased until the next test interruption. This behavior is likely the result of insufficient cutting and plugging of the drill bit, thus increasing the torque necessary to advance the borehole. A lower rotation rate led to lower penetration rates in materials that were not clay. The rotation rate did not seem to affect the advance drilling rate in clay; however, the rotation rate is an important parameter to allow the drill bit to cut and evacuate the cuttings efficiently without plugging the drill bit.

8.3. Perspectives and recommendations

With any emerging technology like MWD in the US, there are still some challenges to overcome:

- Technical challenges: Measuring the torque and downforce at the top of the drill string will be key to helping develop relationships for soil and rock using MWD parameters, similar to other traditional testing methods such as CPTu. Fortunately, at least two of those sensors have become available in the last year.
- Development of an MWD US standard (in progress): Implementing a test standard will provide MWD users with guidelines and drilling recommendations for uniform application of the technique. Standardizing the use of MWD would allow for more consistent comparisons between drillers, drill rigs, and drilling profiles in distinct regions, thus allowing future databases to identify and quantify geological materials.
- Diffusing the technology: The use of MWD in the US is very recent, with current implementation by only a few DOTs and geotechnical companies. The FHWA, through the Every Day Counts initiative and the State Transportation Innovation Councils incentive program, has funded the purchase and installation of MWD equipment for several state transportation agencies.
- Convincing people: The initial cost of the system (between $30-40k depending on the number of sensors) for a complete setup is minimal and comparable to most other in situ systems. The benefits outweigh this initial cost, as they will significantly improve drilling quality and the data obtained from site investigations, leading to safer and more economical geotechnical structures. MWD also provides geotechnical logs that are more detailed and easier to visualize. The MWD Users Group has helped spread information about MWD across the country and internationally, thus increasing the interest in both the public and

private sectors. Another great benefit is that MWD data can be uploaded to exchange systems such as DIGGS, making the information available to engineers, researchers, students, and the public.

Based on the conclusions obtained in this work, the following recommendations can be provided:

- The reference values for drilling parameters presented in this report should be expanded as additional data is collected by the NHDOT to provide a larger database that could ultimately identify geological materials more efficiently. Obtaining a large database on different geological conditions could ultimately help identify geological materials more efficiently, reducing the need for continuous SPT sampling in fewer borehole locations.
- The overburden and existing hydrostatic pressure may be key factors in normalizing drilling or compound drilling parameters for future analysis of extensive data sets, especially when drilling down to more significant depths.
- Compound drilling parameters measured while coring on rock can be directly compared to results from unconfined compression or point load tests on the retrieved cores at corresponding depths. Creating a large database may assist in determining the type or resistance of a given rock based on empirical relationships between the drilling energy and standardized geotechnical tests on rock.
- The effect of parameters imposed by the drilling method (e.g., drilling tool or drilling fluid) must also be evaluated, in addition to comparing drilling profiles obtained by different drillers at a relatively homogeneous site.

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APPENDIX A. MWD TESTING PROCEDURE

This section presents the operating test procedure for the NHDOT MWD system, shown in Figure A.1. A separate version of this manual has also been delivered to the NHDOT MWD drilling crew.

Figure A.1. Measurement While Drilling equipment at the New Hampshire Department of Transportation, USA.

2) Setting up the equipment

1.1) Setting up the data logger

a) Support the MWD data logger on a tripod or other support. Please ensure the system is securely in place and protected from possible rainfall. It is suggested that it be placed close to the driller so that they can also monitor the data collected in real time.

b) Connect the grey wire from the MWD junction box (Figure A.1a) to the data logger (Figure A.1b).

c) Turn on the junction box switch (Figure A.2a – up = on; down = off).

d) Turn on the data logger by pressing the button on the left-hand side of the tablet (location shown in Figure A.2b).

e) If the data logger displays a red light (Figure A.2c), please check the connection between the junction box and its power source. The tablet should work normally when a constant green light is displayed.

f) Please ensure the flow meter (Figure A.1h) was installed on the drill rig to obtain flow measurements.

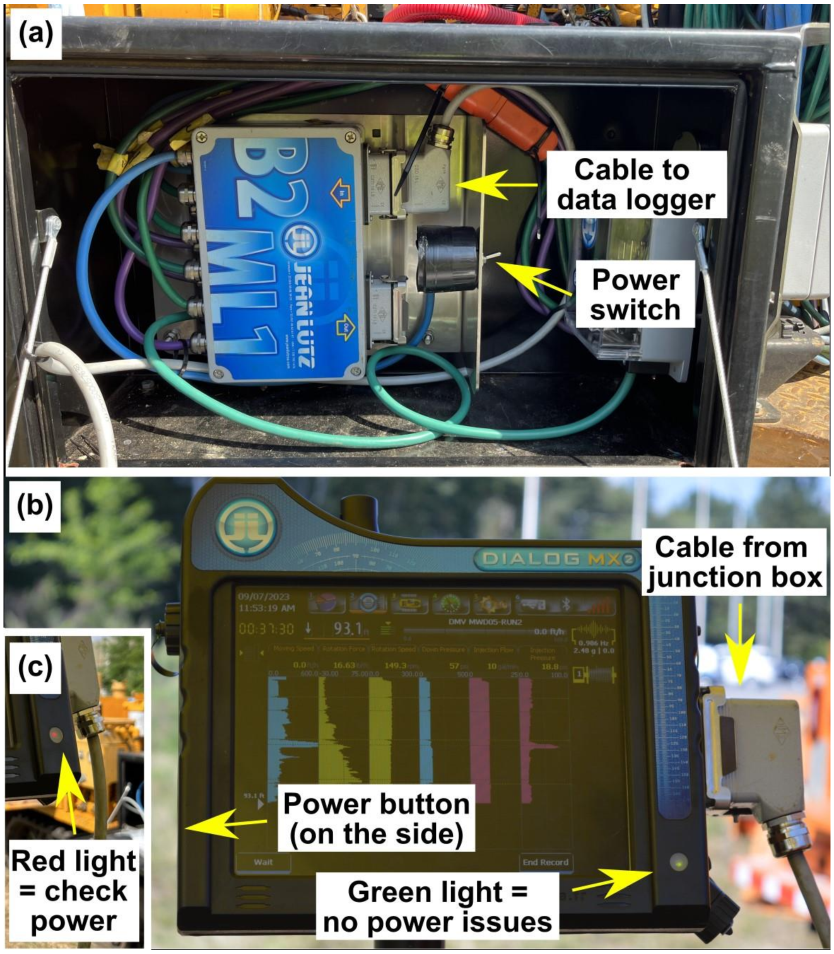


Figure A.2. (a) Junction box power switch and wire connecting to (b) the data logger. The power source should be checked if the data logger displays a red light (c).

1.2) <u>Setting up the wireless torque sensor (from user guide by MWD One – manufacturer)</u>

a) The wireless torque sensor has two covers. The first cover (Figure A.3a) is a translucent white cover that should never be removed. It protects the wireless data transmitter.

b) The second cover is black and must be removed to turn on and off the wireless torque sensor (Figure A.3b).

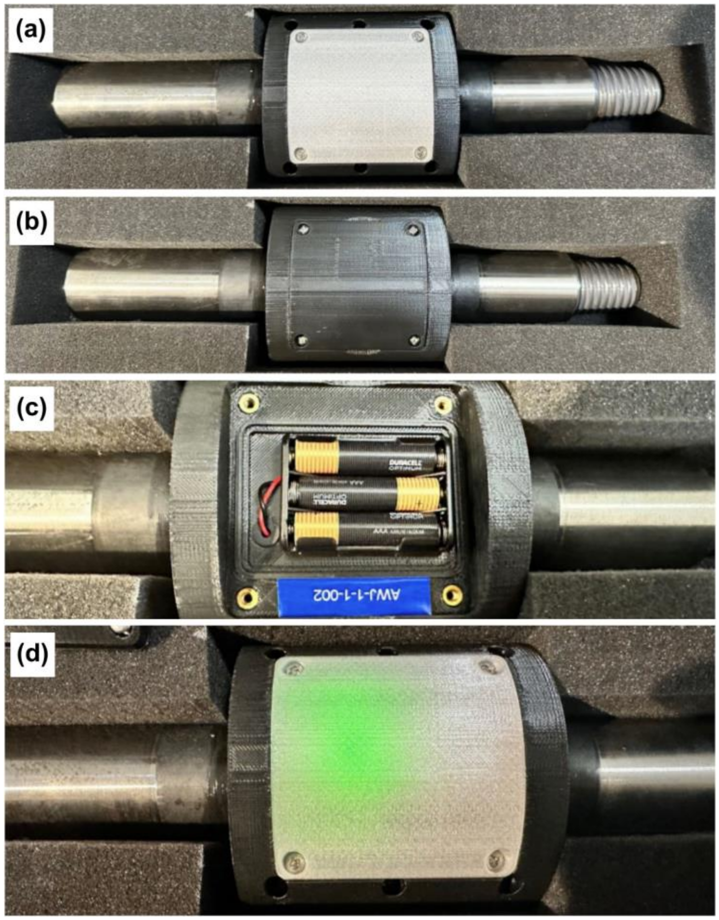


Figure A.3. (a) Data transmitter side of the drill rod; (b) battery pack side of the drill rod; (c) battery cover removed, displaying batteries placed in the holder; and (d) data transmitter slowly pulsing green, indicating the sensor is idle.

i. Remove the black cover and place three AAA batteries into the battery holder (Figure A.3c). Place the cover back on the drill rod and tighten down the screws to secure the cover in place. Do not over-tighten the cover; this may result in cracking.

ii. Once the batteries are placed in the holder and the data logger is powered on the wireless torque sensor is ready to be used (Figure A.3d). The LED codes for the data transmitted are listed here:

- *Rapid green flashing on start-up:* The wireless sensor is booting up,
- *Slow green pulse (1 per second):* The wireless sensor is idle and waiting for a command,

- *1 green blink every 2 seconds:* The wireless sensor is sampling,
- *Blue LED during sampling:* The wireless sensor is resynchronizing,
- Red LED: built-in test error.

Please note that, when outdoors, it can be difficult to see the LED codes well under the sun. In these cases, place the drill rod back in the storage case and partially close the lid to block out the sunlight. You should be able to see the LED codes if necessary to debug any connection issues.

iii. The wireless torque sensor communicates with the PI Box (Figure A.1c), installed next to the junction box on the NHDOT drill rig. The LORD flash drive in the PI Box also provides LED codes that can indicate the status of the wireless sensor (Figure A.4). The LED codes for the LORD gateway are listed here:

- *Green:* gateway is powered and idle,
- *Flashing blue:* sampling data (Fig. 4),
- *Pulsing green:* stopping sampling,
- *Flashing red:* warning – another gateway beacon is detected on the same frequency.

Figure A.4. The PI Box shows the LORD Microstrain gateway with a flashing blue LED code, indicating that the wireless torque sensor is powered on and paired with the PI Box and data logger.

i. To turn off the wireless torque transducer, remove the center battery and place the cover back on (Figure A.5). Three new AAA batteries should provide approximately 80 hours of continuous sampling.

Please note that removing the two outer batteries in the holder can be difficult. This is intentional. The manufacturer wanted to ensure the batteries did not dislodge during drilling due to vibration.

Figure A.5. The center battery was removed to power off the wireless torque sensor.

3) Creating a new test file

a) Select tab “2” at the toolbar at the top of the data logger screen (Figure A.6).

b) Under “Jobsite,” provide the name of the test location (e.g., town or site name). The fields “contract” and “section” must also be filled with test site or contractor information.

   i. Each combination of Jobsite + Contract + Section will create a new folder for storing data files from the same job site, contract, and section.

c) Provide the borehole ID and start depth in the quadrant below the site information (orange box in Fig. 6, lower left of screen).

   i. It is recommended that borehole IDs be provided indicating the borehole's number and the current data file for that borehole. For example, “B01-RUN1” would indicate the first run at borehole B01. If data collection stops and a new data file is created to continue sampling data from the same borehole, update the start depth and change the borehole ID to “B01-RUN2”. It will help with merging data files in the future.

   ii. The “Target Depth” box can be left blank. It helps the driller identify the target depth more easily by drawing a horizontal red line at the desired depth on the screen. It does not stop data recording at the set target depth. Data is sampled normally past the set depth unless the user manually closes the data file.

   iii. The auger length should be defined at 5ft for 5 ft rods, but rods of other lengths can be used regardless of the predefined auger length.

iv. After all test information has been provided, the user can press “Start” to create the data file. *Please note that creating a data file does NOT start the measurements automatically.*

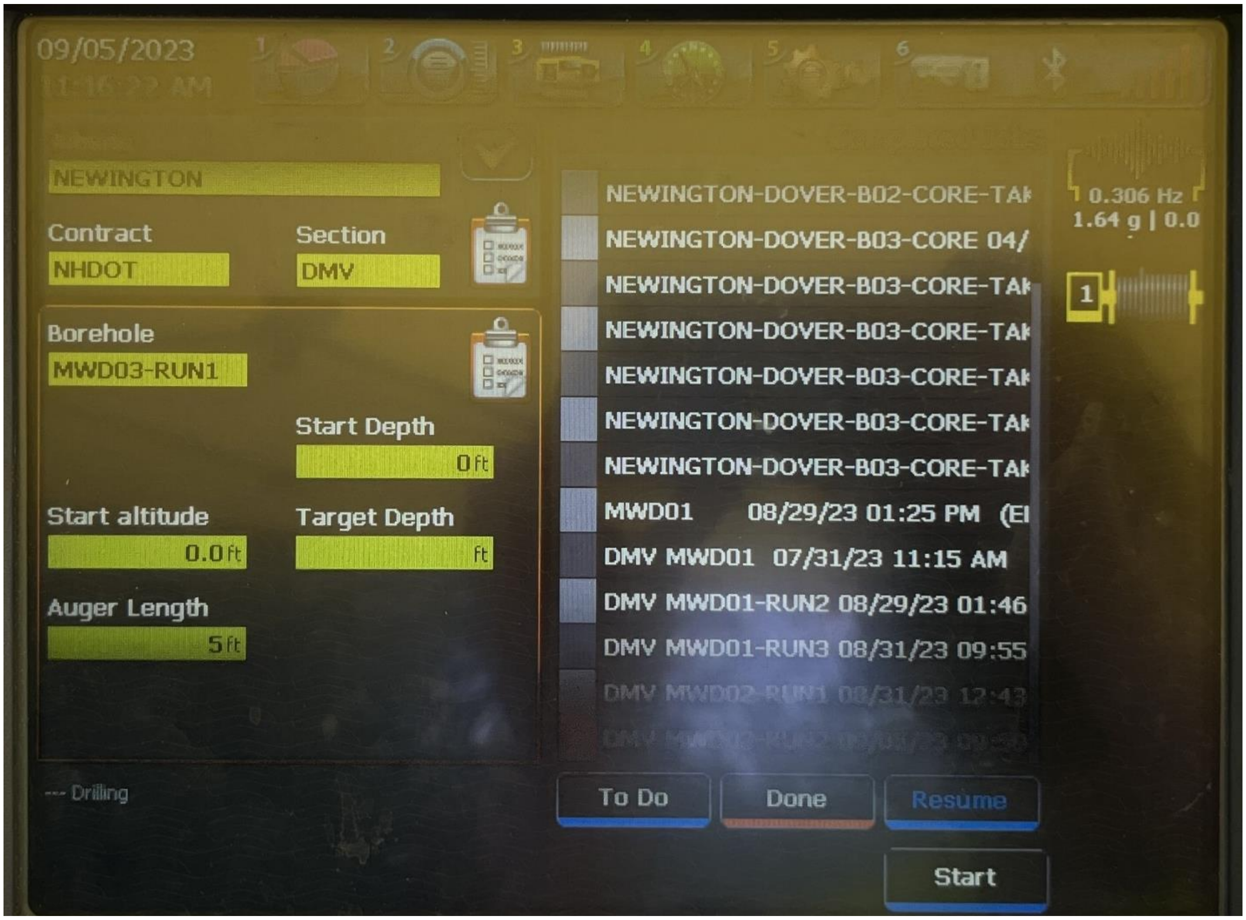


Figure A.6. Creating a new data file under tab “2” in the data logger.

v. It is also possible to resume sampling on a previous data file by selecting the desired file on the list shown on the right (Figure A.6) and pressing “Resume.” Data recording will be resumed at the exact depth at which the file was saved previously. However, creating a new data file and adding the run number (step 2c) is recommended.

4) Before drilling – Write down important test information

As discussed in section “1. What is MWD?”, other variables are also important in MWD data analysis and are not recorded in the data logger. Therefore, additional test information should be written on a data sheet (Figure A.7).

i. Please provide as much information as possible in the fields outlined in red in Figure A.7.

ii. Before drilling, it is essential to provide the drilling tool type/material and diameter and its approximate wear. If possible, please take a picture of the bit.

MEASUREMENT WHILE DRILLING *Adapted from EN ISO 22476-15*	**Driller(s):** ________________ **Operator(s):** ________________	**Date:** ____________________ **Water table:** ______________ ft **Tool:** ____________________
Company: NHDOT **Project:** ____________________ **Location:** ____________________ **Borehole:** ____________________	**Machine manufacturer:** **Model:** **Serial N°:**	**Wear before drilling:** 0 - 20 - 40 - 60 - 80 - 100 % **Wear after drilling:** 0 - 20 - 40 - 60 - 80 - 100 %
Rods: ____________________ **Diameter:** ____________________ **Weight:** ____________________ **Length:** ____________________	**Flushing medium** Air ☐ Mud ☐: ________________ Foam ☐	**Position (precision)** **X:** ______ (______) ft **Y:** ______ (______) ft **Z:** ______ ft
Depth / Time From: _______/______:______ AM PM To: _______/______:______ AM PM	**Drilling method** Rotation ☐ Rotarypercussion ☐	**MWD Torque sensor** TICOR (Jean Lutz) ☐ MWD One ☐

Name of data file:
Remarks (interruptions, obstructions, difficulties, etc.):
Reason for drilling termination:

Figure A.7. Relevant test information should be written down in a data sheet for each generated data file.

5) Recording MWD data

a) After creating a new data file, the data logger will display a yellow screen (Figure A.8). The user can select to display either three parameter graphs and a column showing the instantaneous values for all parameters (Figure A.8a) or six parameter graphs (Figure A.8b).

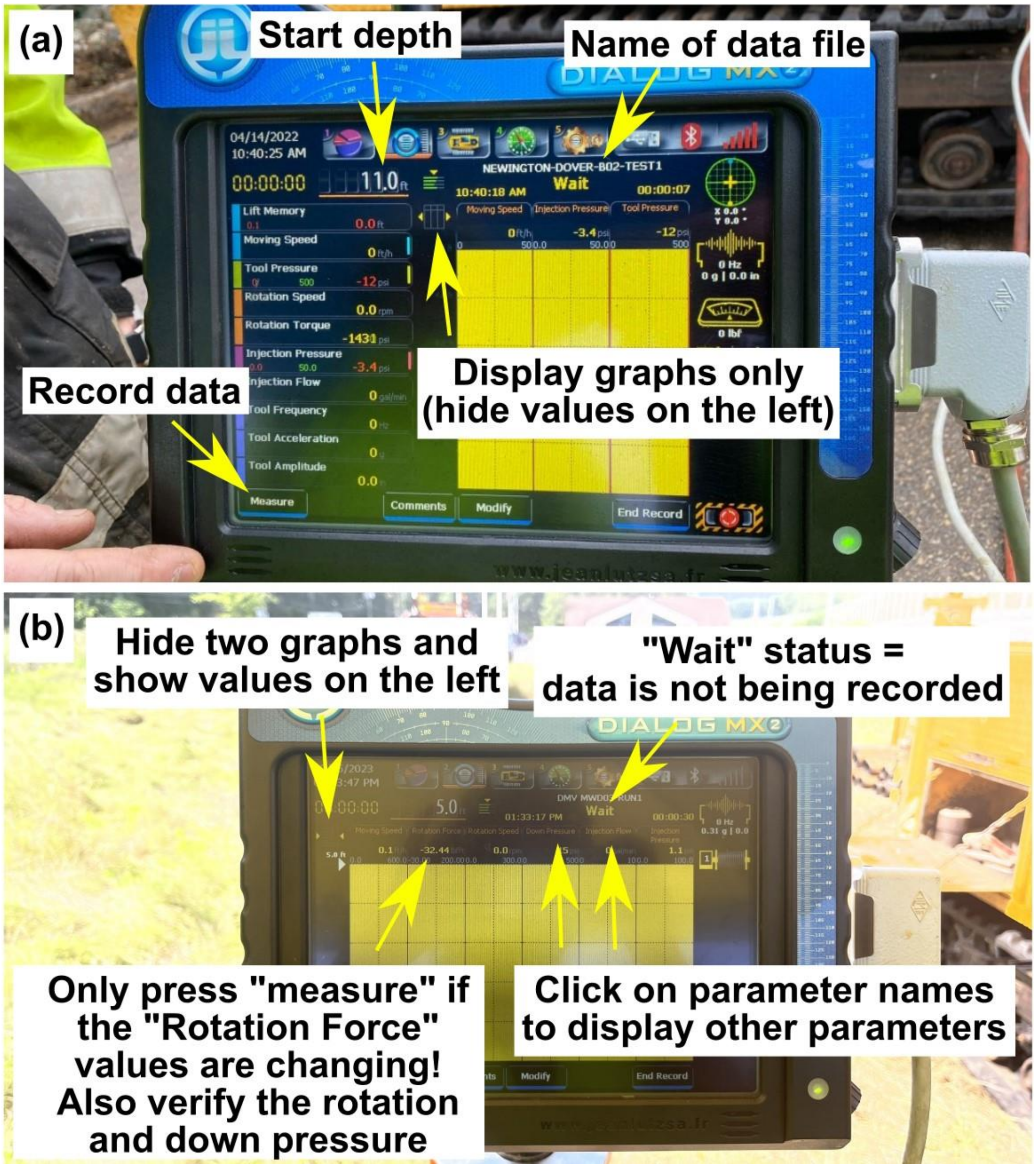


Figure A.8. (a) Yellow screen indicating that the data logger is on “wait” status – waiting for the user to press “measure” to start recording data. (b) The user should only start recording data after verifying that the sensors are paired with the data logger.

Each graph plots a given parameter vs. depth. Click on a parameter to display other measurements. It is recommended that you monitor the moving speed, rotation speed, rotation force, down pressure, injection flow, and injection pressure.

b) Verify if the torque and thrust force instantaneous values (under "Rotation Force" and "V Force") read sufficiently low values (near zero before drilling). ***If these values do not read approximately zero, please stop immediately and follow the procedure in Annex A – wireless torque/thrust sensor calibration.***

c) Start rotating without advancing the drill bit to ensure that the torque sensor is not idle. If the rotation force measurements do not change slightly, the sensor has not been paired with the data logger. Please wait a few minutes, as sometimes the sensor may take a while to pair with the PI Box and then the data logger. If the problem persists, check if the batteries are still in place. The rig vibration might have displaced them. If it still does not work, it is most likely that its current AAA batteries need to be replaced.

d) Check if the rotation speed is reading a non-zero value. If the data file was created several minutes before the drill rig was started, it takes a couple of minutes for the junction box to pair with the data logger. Please wait until the connection has been reestablished. This may also happen to resume measurements if drilling has been paused for several minutes.

e) After verifying that all parameters are being measured, the test operator may select "Measure" on the data logger (Figure A.8a). Press this button before advancing the borehole with the drill bit at the exact provided start depth (e.g., on the ground surface for a 0 ft start depth). A screen similar to Figure A.9 will be displayed.

f) Any changes observed in cuttings (e.g., change of material or color) should be written down in the datasheet, as well as the depths at which these changes occur. This information may be particularly helpful in data interpretation.

g) Advance the borehole to the maximum depth possible, and press "wait" (Figure A.9) <u>before</u> adding a new rod. The screen will then display the same graphs, but under "wait" mode (yellow screen, Figure A.10).

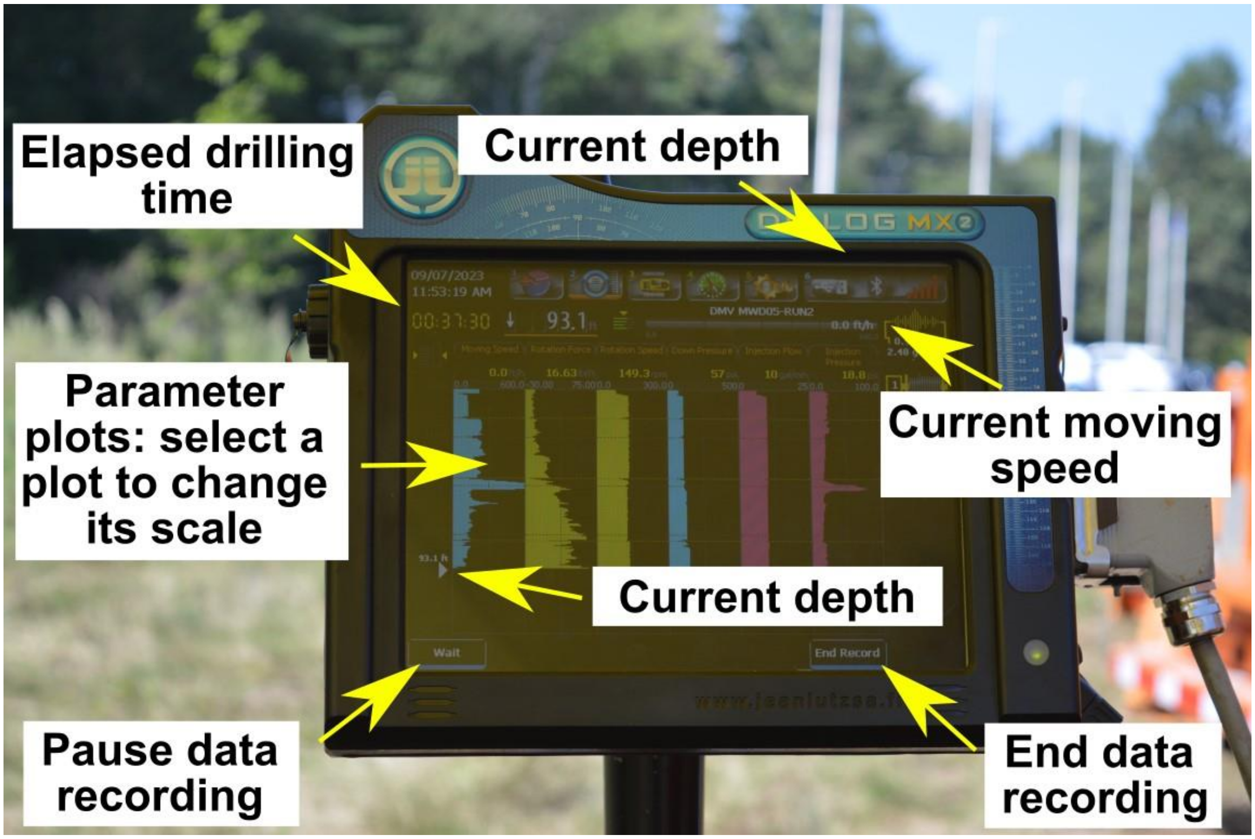


Figure A.9. Measurement screen indicating that MWD data is being measured and recorded.

Figure A.10. The yellow measurement screen indicates that MWD data collection is paused while a new rod is added, or drilling operations are paused.

h) After adding a new rod, please verify if all parameters are being measured (steps 4b – 4d). When the driller is ready to continue drilling, please select "Measure" again. This must be done before the driller starts advancing the borehole. As shown in Figure A.9, a black screen will then be displayed again.

i) Repeat steps 4e) through 4h) until the final depth has been reached.

j) To terminate a test, press "End Record" at the bottom right of the data logger screen (Figures 3.9 and 3.10).

k) A window to verify test information will appear (Figure A.11). To save the test, select the green checkmark ✅ and wait until the popup window disappears (Figure A.12).

l) Press "Next" to go back to the main screen, where a new data file can then be created (Figure A.13). The current borehole ID will be inactive (red). To create a new data file, change the site information or update the borehole ID (new borehole, e.g., B02-RUN1, or new run, e.g., B01-RUN2).

Figure A.11. Popup window at the end of a test. Select the green checkmark to save it.

Figure A.12. After the test has been completed, press “Next” to leave the measurements screen.

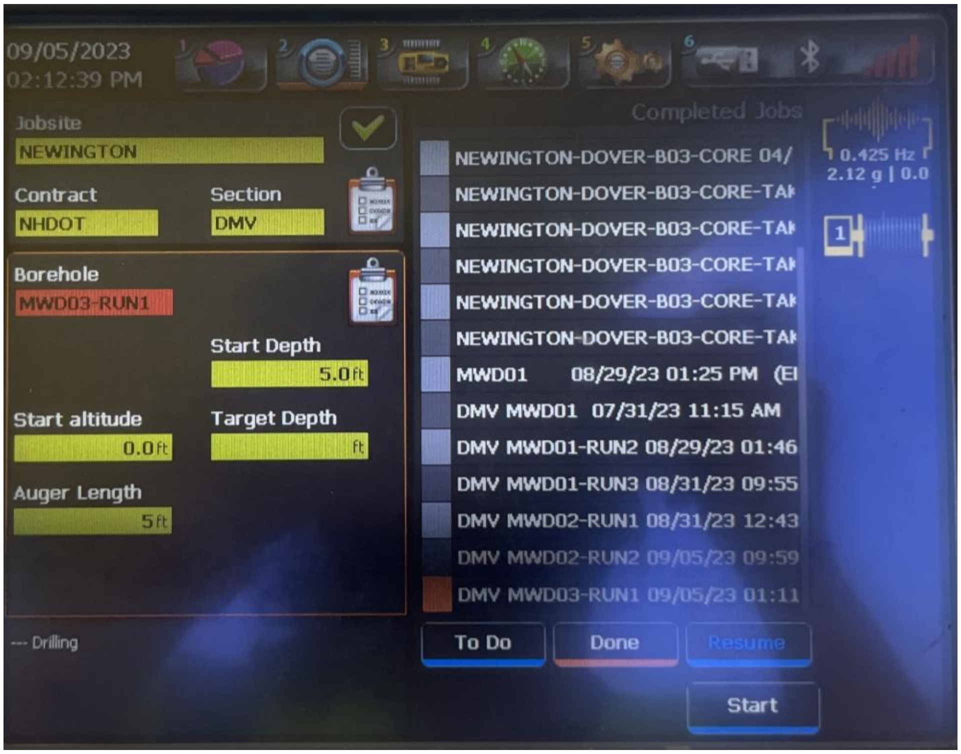


Figure 13. Main screen after the test has been saved.

6) After drilling – Write down important test information

a) Write down on the datasheet the reason for test termination (e.g., reached bedrock or the depth was the same as other SPT tests…).

b) Also, on the data sheet (Figure A.7), take notes on the drill bit condition after the test, and if it has significantly worn out, please take pictures.

c) Double-check if the measured depth in the data logger is the same as the actual depth (including the length of the drill bit). If they are not the same, please write down the actual depth on the datasheet. A depth calibration will then be necessary (Figure A.14).

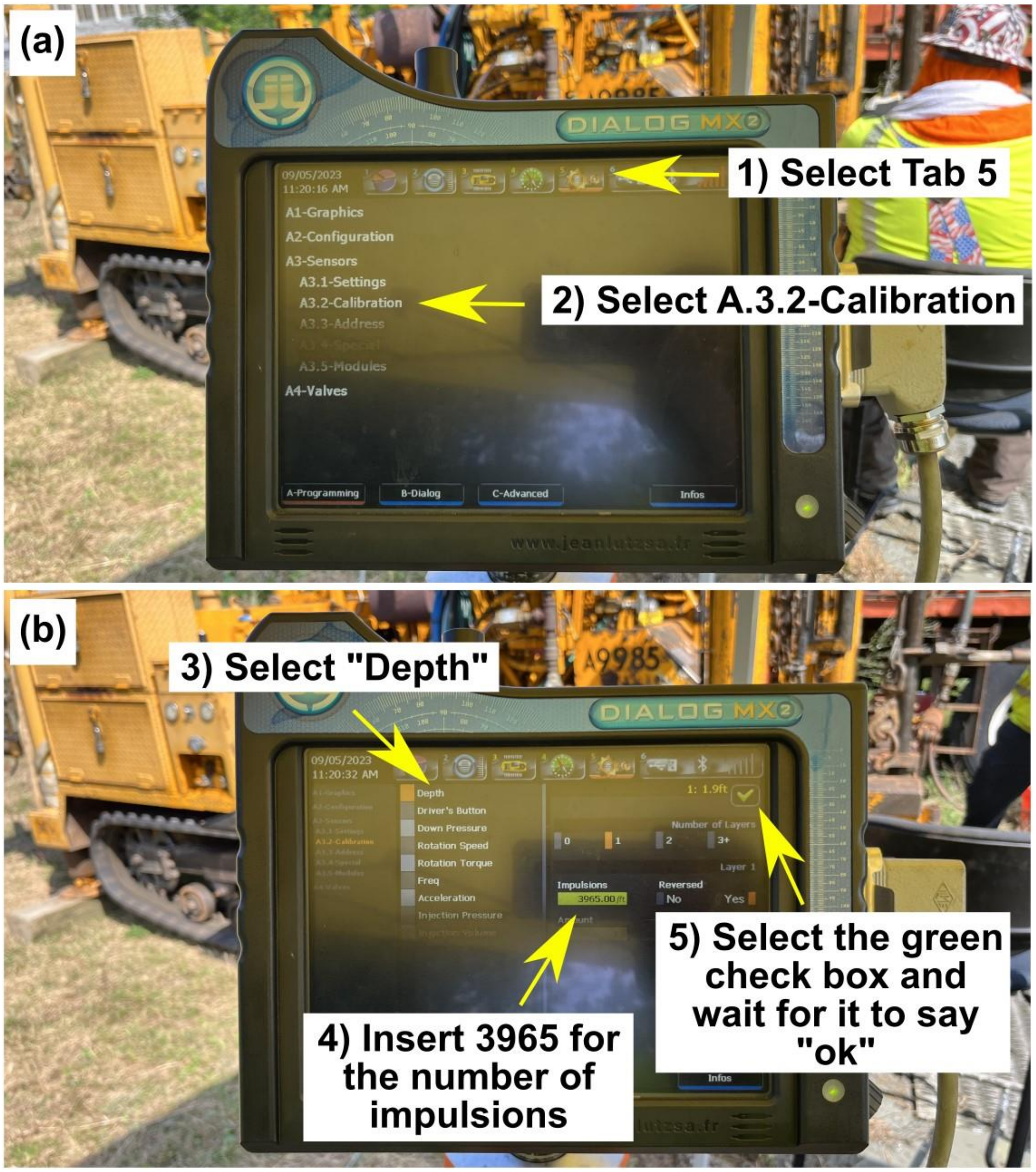


Figure A.14. Depth sensor calibration.

7) Downloading a test file

a) To download a test file to a flash drive, connect the flash drive to the USB port on the upper left lateral side of the data logger (Figure A.15).

b) Select Tab 6 at the upper bar on the data logger, where there is a flash drive and a Bluetooth icon.

c) Select a job site (test folder) to download. The selected folder will display an orange box on the left side.

Figure A.15. Flash drive in data logger USB port.

d) Then, select "USB" on the upper right side, and all data files in the selected folder will be transferred to the flash drive. This may take a few minutes.

e) If you would like to download one specific data file instead and not an entire folder, select "Jobs" at the lower left portion of the screen, and the data files for the selected folder will be displayed (Figure A.17).

f) The flash drive may be removed after all desired folders and/or files have been downloaded.

Figure A.16. Tab 6 – Export a data folder or file.

Figure A.17. Tab 6 – Selecting a data file under “Jobs” in the lower left tab.

g) To delete a test file or folder (please ensure that the downloaded files are readable and properly stored before deleting them):

i. Select the desired file or folder, and press the “REMOVE” button on the bottom right of the screen.

ii. The DIALOG will replace the “REMOVE” button with a “CONFIRM” button. If the delete button is pressed accidentally, wait for a few seconds; the button will reset, and the file will not be deleted.

iii. It is not recommended to delete test files until they have been previously opened on a computer and stored elsewhere.

h) To replay a test on the MWD data logger:

i. Select a single test data file on Tab 6.

ii. Press “Replay” to watch a full rest replay (Figure A.17).

iii. The replay speed can be increased as desired (Figure A.18).

Figure A.18. Tab 6 – Replaying a test file.

APPENDIX B. MATLAB CODE FOR MWD DATA PROCESSING

```
clc;
clear;
close all;

%% Read raw data
matrix = xlsread('rawdata.xlsx'); % Reads the raw MWD data

% Replace NaN values with 0
matrix(isnan(matrix)) = 0;

% Extract depth values from the first column
depth_values = matrix(:, 1);

% Initialize a logical index vector to keep track of rows to keep
keep_rows = true(size(matrix, 1), 1);

% Iterate over depth values and remove rows where depth decreases
for i = 2:length(depth_values)
    if depth_values(i) <= depth_values(i-1)
        keep_rows(i) = false;
    end
end

% Filter the matrix based on the logical index vector
data = matrix(keep_rows, :);

z = data(:,1); % m
Va = data(:,2); %m/h
Pe = data(:,3); % bar
Fe = data(:,4); % N
Vr = data(:,5); % rpm
T = data(:,6); % N-m
f = data(:,7); % Hz
a = data(:,8); % m/s^2
Mp = data(:,9); % bar
Mf = data(:,10); % L/min

data = xlsread('rawSPT'); % Reads the SPT data
depth_SPT = data(:,1);
depth_SPT = depth_SPT/0.3048;
SPT = data(:,2);
R = data(:,3);
water = data(1,4);

D = 0.08; % m
S0 = pi*(D^2)/4; % m^2

%% Convert raw data from SI to imperial units
D_ = D*39.37; % in
S0_ = pi*(D_^2)/4; %in^2
z_ = z/0.3048; % ft
Va_ = Va*39.37/60; % in/min
Pe_ = Pe*14.5038*6.8; % lbs, after multiplying by area of cylinders
Pe_ = Pe_ / S0_;
```

```
Fe_ = Fe*0.224809/1000; % kips
Vr_ = Vr; % rpm
T_ = T*8.8507457916/1000; % k-in
f_ = f; % Hz
a_ = a/0.3048; % ft/s^2
Mp_ = Mp*14.5038; % psi
Mf_ = Mf/3.78; % gpm


Va = Va/60; %m/min
Pe = Pe/10; % MPa
Pe = Pe*0.00438709/S0; % MPa
Fe = Fe/1000; % kN
Vr = Vr; % rpm
T = T; % N-m
f = f; % Hz
a = a; % m/s^2
Mp = Mp*100; % kPa
Mf = Mf; % L/min


%% Calculate compound parameters

L = length(z);
for i = 1:L

% Specific energy

    e(i) = (Fe(i)/1000/S0) + (2*pi*Vr(i)*T(i)/1000000)/(S0*Va(i));
    e_(i) = (Fe_(i)/S0_) + (2*pi*Vr_(i)*T_(i))/(S0_*Va_(i));

    e2(i) = Pe(i) + (2*pi*Vr(i)*T(i)/1000000)/(S0*Va(i));
    e2_(i) = Pe_(i)/1000 + (2*pi*Vr_(i)*T_(i))/(S0_*Va_(i));

% Drillability strength

    Ds(i) = (64*Vr(i)*((T(i)/1000000)^2))/(Fe(i)/1000*Va(i)*(D^3));
    Ds_(i) = (64*Vr_(i)*(T_(i)^2))/(Fe_(i)*Va_(i)*(D_^3));

    Ds2(i) = (64*Vr(i)*((T(i)/1000000)^2))/((Pe(i)*S0)*Va(i)*(D^3));
    Ds2_(i) = (64*Vr_(i)*(T_(i)^2))/((Pe_(i)*S0)*Va_(i)*(D_^3));

% Somerton Index

    Sd(i) = (Fe(i)/1000/S0)*(Vr(i)/(Va(i)/60))^0.5; % unitless
    Sd_(i) = 1000*(Fe_(i)/S0_)*(Vr_(i)/Va_(i))^0.5; % unitless

    Sd2(i) = Pe(i)*(Vr(i)/(Va(i)/60))^0.5;
    Sd2_(i) = Pe_(i)*(Vr_(i)/Va_(i))^0.5;

% Soil-rock resistance

    Rsr(i) = Fe(i)/1000/(S0*Va(i));
    Rsr_(i) = Fe_(i)/(S0_*Va_(i));

    Rsr2(i) = Pe(i)/Va(i);
    Rsr2_(i) = Pe_(i)/Va_(i);
```

```
% Exponent method

    E(i) = (log(Va(i)/(Vr(i)*D))/log(Fe(i)/1000*D/T(i)));
    E_(i) = (log(Va_(i)/(Vr_(i)*D_))/log(Fe_(i)*D_/T_(i)));

    E2(i) = (log(Va(i)/(Vr(i)*D))/log((Pe(i)*S0)*D/T(i)));
    E2_(i) = (log(Va_(i)/(Vr_(i)*D_))/log((Pe_(i)*S0_)*D_/T_(i)));

end


% Replace NaN values with 0
e(isnan(e)) = 0.001;
e2(isnan(e2)) = 0.001;
Ds(isnan(Ds)) = 0.001;
Ds2(isnan(Ds2)) = 0.001;
Sd(isnan(Sd)) = 0.001;
Sd2(isnan(Sd2)) = 0.001;
Rsr(isnan(Rsr)) = 0.001;
Rsr2(isnan(Rsr2)) = 0.001;
E(isnan(E)) = 0.001;
E2(isnan(E2)) = 0.001;

% Replace NaN values with 0
e_(isnan(e_)) = 0.001;
e2_(isnan(e2_)) = 0.001;
Ds_(isnan(Ds_)) = 0.001;
Ds2_(isnan(Ds2_)) = 0.001;
Sd_(isnan(Sd_)) = 0.001;
Sd2_(isnan(Sd2_)) = 0.001;
Rsr_(isnan(Rsr_)) = 0.001;
Rsr2_(isnan(Rsr2_)) = 0.001;
E_(isnan(E_)) = 0.001;
E2_(isnan(E2_)) = 0.001;

e_ = transpose(e_);
e2_ = transpose(e2_);
Ds_ = transpose(Ds_);
Ds2_ = transpose(Ds2_);
Sd_ = transpose(Sd_);
Sd2_ = transpose(Sd2_);
Rsr_ = transpose(Rsr_);
Rsr2_ = transpose(Rsr2_);
E_ = transpose(E_);
E2_ = transpose(E2_);

e = transpose(e);
e2 = transpose(e2);
Ds = transpose(Ds);
Ds2 = transpose(Ds2);
Sd = transpose(Sd);
Sd2 = transpose(Sd2);
Rsr = transpose(Rsr);
Rsr2 = transpose(Rsr2);
E = transpose(E);
E2 = transpose(E2);
```

```
%% Plot graphs - FORCE (Imperial)

depth = z_;
num_params = 16; % Number of soil parameters
params = [Va_, Pe_, Fe_, Vr_, T_, f_, Mp_, Mf_, e_, Sd_]; % Random sample
data, replace with actual data
param_titles = {'u (in/min)','Pe (psi)','Fe (kips)','Vr (RPM)','T (in-
kips)','f (Hz)','P (psi)','Qi (GPM)','e (ksi)','Sd','N_S_P_T
(blows/ft)','Recovery (%)'};
params_SPT = [depth_SPT, SPT, R];


% Define less repetitive colors with 60% transparency for filling
fill_colors = [
    1.0 0.0 0.0 0.5;    % Red 1
    0.0 1.0 0.0 0.5;    % Green 2
    0.0 0.0 1.0 0.5;    % Blue 3
    1.0 1.0 0.0 0.5;    % Yellow 4
    0.0 1.0 1.0 0.5;    % Cyan 5
    1.0 0.0 1.0 0.5;    % Magenta 6
    0.0 0.5 0.5 0.5;    % Teal 8
    0.5 0.0 0.5 0.5;    % Purple 9
    0.8 0.5 0.0 0.5;    % Brown 13
    0.5 0.5 0.5 0.5;    % Gray 13
    0.5 0.5 0.5 0.5;    % Gray 13
    0.5 0.5 0.5 0.5;    % Gray 13
    0.8 0.5 0.0 0.5;    % Brown 13
    1.0 0.5 0.5 0.5;    % Pink 15
    0.5 0.0 1.0 0.5;    % Indigo 16
];

% Reverse the order of depth values and corresponding measurements
depth = flipud(depth);
params = flipud(params);

% Create figure
figure('Units', 'inches', 'Position', [0, 0, 11, 8.5], 'PaperOrientation',
'landscape');

% List of available nice numbers for x-axis limits
nice_numbers = [1, 2, 4, 8, 10, 20, 30, 40, 50, 60, 80, 100, 200, 300, 400,
500, 600, 700, 800, 900, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000,
9000, 10000, 15000, 20000, 25000, 30000, 35000, 40000, 45000, 50000, 60000,
70000, 80000, 90000, 100000, 10000000, 10000000, 10000000];

% Define the total width for subplots and heights
total_width = 0.9;
total_height = 0.8;

% Define the gap between subplots
gap = 0.01;

% Calculate the width for normal and double-width subplots
normal_width = (total_width - 11 * gap) / (10 + 2 * 2); % 10 normal subplots
+ 2 double-width subplots (each counts as 2)
double_width = 2 * normal_width;
```

```
% Calculate the positions for each subplot
positions = [
    0.05, 0.1, normal_width, total_height; % Subplot 1
    0.05 + normal_width + gap, 0.1, normal_width, total_height; % Subplot 2
    0.05 + 2 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 3
    0.05 + 3 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 4
    0.05 + 4 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 5
    0.05 + 5 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 6
    0.05 + 6 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 7
    0.05 + 7 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 8
    0.05 + 8 * (normal_width + gap), 0.1, double_width, total_height; %
Subplot 9 (double width)
    0.05 + 8 * (normal_width + gap) + double_width + gap, 0.1, double_width,
total_height; % Subplot 10 (double width)
    0.05 + 8 * (normal_width + gap) + 2 * (double_width + gap), 0.1,
normal_width, total_height; % Subplot 11
    0.05 + 9 * (normal_width + gap) + 2 * (double_width + gap), 0.1,
normal_width, total_height; % Subplot 12
];

% Plot line plots and fill the area between line plots and y-axis using
trapezoids
for i = 1:12
    ax = axes('Position', positions(i, :));

    % Determine the maximum value for the x-axis
    if i < 11
        max_param_value = max(max(params(:, i)), 1);
    elseif i == 11
        max_param_value = max(params_SPT(:,2));
    elseif i == 12
        max_param_value = max(params_SPT(:,3));
    end
    nice_max_param_value = nice_numbers(find(nice_numbers >= max_param_value,
1)); % Find the closest largest nice number

    if i < 11
        if nice_max_param_value > 1000
            exp_nice_max_param_value = nice_numbers(find(nice_numbers >=
nice_max_param_value, 1, 'first'));
            xlim([0, exp_nice_max_param_value]);
        else
            xlim([0, nice_max_param_value + 0.1 * nice_max_param_value]);
        end
    end

    if i < 11
        for j = 1:size(params, 1)-1
            x_values = [0, params(j, i), params(j + 1, i), 0];
            y_values = [depth(j), depth(j), depth(j + 1), depth(j + 1)];
```

```
            patch(x_values, y_values, fill_colors(i, 1:3), 'FaceAlpha',
fill_colors(i, 4), 'EdgeColor', 'none');
        end
    end
    hold on;
    if i < 11
        plot(params(:, i), depth, 'Color', 'k', 'LineWidth', 0.5);
    elseif i == 11
        scatter(SPT, depth_SPT, 'Marker', 'o', 'MarkerEdgeColor', 'k',
'MarkerFaceColor', 'k');
        SPTs = max(SPT);
        nice_max_SPT = nice_numbers(find(nice_numbers >= max(SPTs), 1));
        xlim([0, nice_max_SPT + 0.1 * nice_max_SPT]);
    elseif i == 12
        scatter(R, depth_SPT, 'Marker', 'o', 'MarkerEdgeColor', 'k',
'MarkerFaceColor', 'k');
        nice_max_SPT = nice_numbers(find(nice_numbers >= max(R), 1));
        xlim([0, 100]);
    end
    xlabel(strrep(param_titles{i}, ' ', sprintf('\n')), 'FontSize', 8);

    ylim([min(depth), max(depth)]);
    if i == 1
        ylabel('Depth (ft)', 'FontSize', 8);
    else
        set(ax, 'YTickLabel', []);
    end
    set(ax, 'XAxisLocation', 'top', 'YDir', 'reverse');
    grid on;

    if i < 12
        half_max_param_value = nice_max_param_value * 0.5;
        xticks([0, half_max_param_value, nice_max_param_value]);
        xtickangle(90);
    elseif i == 9 || i == 10 % For subplots 9 and 10
        xtick_vals = linspace(0, nice_max_param_value, 5); % 5 tick marks
        xticks(xtick_vals);
        xtickangle(90);
    elseif i == 12
        xticks([0, 50, 100]);
        xtickangle(90);
    end
end

% Add the title above the subplots using annotation
annotation('textbox', [0 0.95 1 0.05], 'String', 'MWD - Bridgewater NH - B01
- Drilling', ...
    'EdgeColor', 'none', 'HorizontalAlignment', 'center', 'FontSize', 10);

filename = 'SiteName_BoreholeID_Drilling_Imperial.png';

% Save the figure as a PNG in high quality
saveas(gcf, filename, 'png');
```

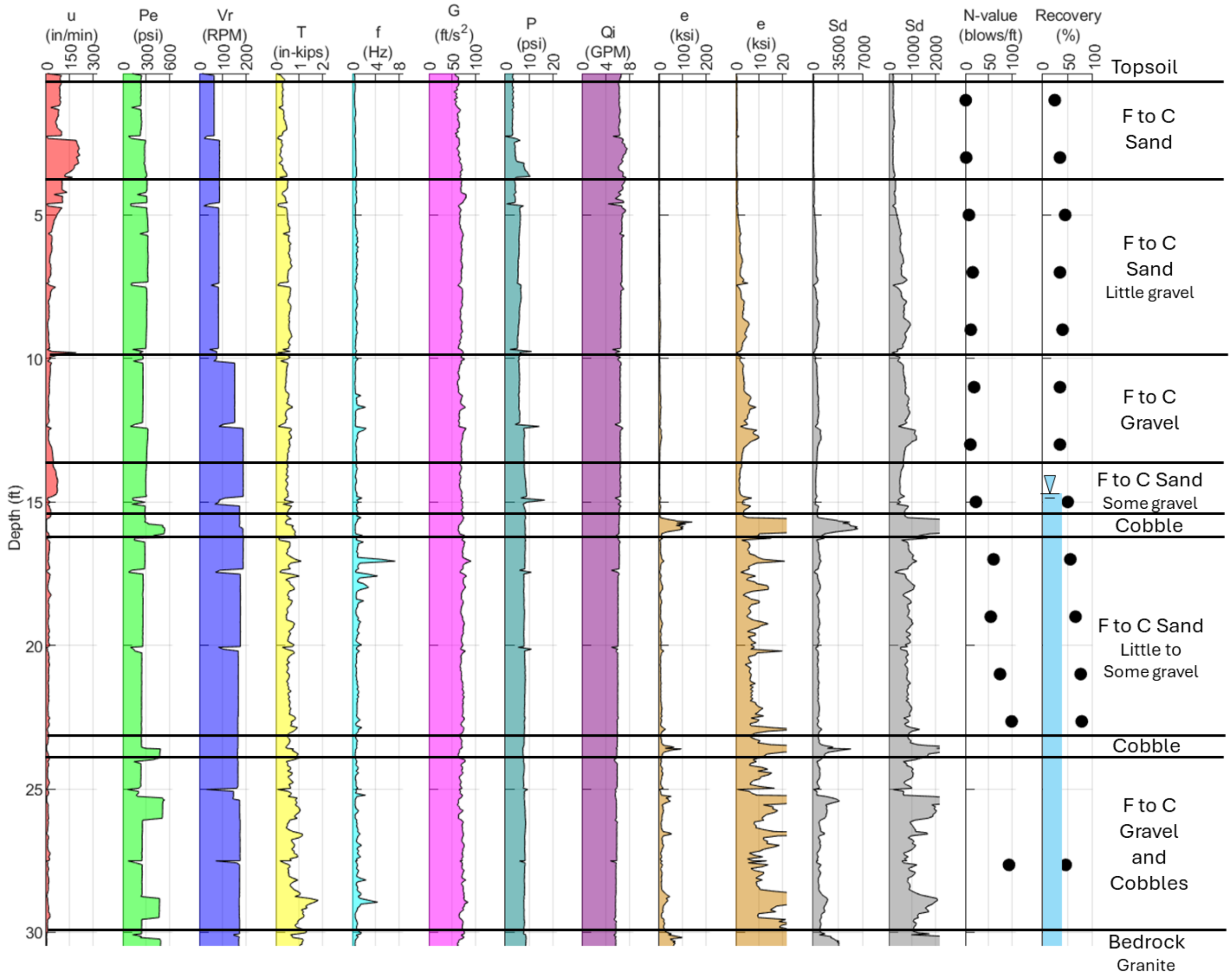
```
%% Plot graphs -- FORCE (SI)

depth = z;
num_params = 16; % Number of soil parameters
params = [Va, Pe, Fe, Vr, T, f, Mp, Mf, e, Sd_, Fe]; % Random sample data,
replace with actual data
param_titles = {'u (m/min)','Pe (MPa)','Fe (kN)','Vr (RPM)','T (N-m)','f
(Hz)','P (kPa)','Qi (L/min)','e (MPa)','Sd','N_S_P_T (blows/30cm)','Recovery
(%)'};
params_SPT = [depth_SPT*0.3048, SPT, R];
% Define less repetitive colors with 60% transparency for filling
fill_colors = [
    1.0 0.0 0.0 0.5;    % Red 1
    0.0 1.0 0.0 0.5;    % Green 2
    0.0 0.0 1.0 0.5;    % Blue 3
    1.0 1.0 0.0 0.5;    % Yellow 4
    0.0 1.0 1.0 0.5;    % Cyan 5
    1.0 0.0 1.0 0.5;    % Magenta 6
    0.0 0.5 0.5 0.5;    % Teal 8
    0.5 0.0 0.5 0.5;    % Purple 9
    0.8 0.5 0.0 0.5;    % Brown 13
    0.5 0.5 0.5 0.5;    % Gray 13
    0.5 0.5 0.5 0.5;    % Gray 13
    0.5 0.5 0.5 0.5;    % Gray 13
    0.8 0.5 0.0 0.5;    % Brown 13
    1.0 0.5 0.5 0.5;    % Pink 15
    0.5 0.0 1.0 0.5;    % Indigo 16
];

% Reverse the order of depth values and corresponding measurements
depth = flipud(depth);
params = flipud(params);

% Create figure
figure('Units', 'inches', 'Position', [0, 0, 11, 8.5], 'PaperOrientation',
'landscape');

% List of available nice numbers for x-axis limits
nice_numbers = [1, 2, 4, 8, 10, 20, 30, 40, 50, 60, 80, 100, 200, 300, 400,
500, 600, 700, 800, 900, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000,
9000, 10000, 15000, 20000, 25000, 30000, 35000, 40000, 45000, 50000, 60000,
70000, 80000, 90000, 100000, 10000000, 10000000, 10000000];

% Define the total width for subplots and heights
total_width = 0.9;
total_height = 0.8;

% Define the gap between subplots
gap = 0.01;

% Calculate the width for normal and double-width subplots
normal_width = (total_width - 11 * gap) / (10 + 2 * 2); % 10 normal subplots
+ 2 double-width subplots (each counts as 2)
double_width = 2 * normal_width;

% Calculate the positions for each subplot
```

```
positions = [
    0.05, 0.1, normal_width, total_height; % Subplot 1
    0.05 + normal_width + gap, 0.1, normal_width, total_height; % Subplot 2
    0.05 + 2 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 3
    0.05 + 3 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 4
    0.05 + 4 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 5
    0.05 + 5 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 6
    0.05 + 6 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 7
    0.05 + 7 * (normal_width + gap), 0.1, normal_width, total_height; %
Subplot 8
    0.05 + 8 * (normal_width + gap), 0.1, double_width, total_height; %
Subplot 9 (double width)
    0.05 + 8 * (normal_width + gap) + double_width + gap, 0.1, double_width,
total_height; % Subplot 10 (double width)
    0.05 + 8 * (normal_width + gap) + 2 * (double_width + gap), 0.1,
normal_width, total_height; % Subplot 11
    0.05 + 9 * (normal_width + gap) + 2 * (double_width + gap), 0.1,
normal_width, total_height; % Subplot 12
];

% Plot line plots and fill the area between line plots and y-axis using
trapezoids
for i = 1:12
    ax = axes('Position', positions(i, :));

    % Determine the maximum value for the x-axis
    if i < 11
        max_param_value = max(max(params(:, i)), 1);
    elseif i == 11
        max_param_value = max(params_SPT(:,2));
    elseif i == 12
        max_param_value = max(params_SPT(:,3));
    end
    nice_max_param_value = nice_numbers(find(nice_numbers >= max_param_value,
1)); % Find the closest largest nice number

    if i < 11
        if nice_max_param_value > 1000
            exp_nice_max_param_value = nice_numbers(find(nice_numbers >=
nice_max_param_value, 1, 'first'));
            xlim([0, exp_nice_max_param_value]);
        else
            xlim([0, nice_max_param_value + 0.1 * nice_max_param_value]);
        end
    end

    if i < 11
        for j = 1:size(params, 1)-1
            x_values = [0, params(j, i), params(j + 1, i), 0];
            y_values = [depth(j), depth(j), depth(j + 1), depth(j + 1)];
            patch(x_values, y_values, fill_colors(i, 1:3), 'FaceAlpha',
fill_colors(i, 4), 'EdgeColor', 'none');
```

```
        end
    end
    hold on;
    if i < 11
        plot(params(:, i), depth, 'Color', 'k', 'LineWidth', 0.5);
    elseif i == 11
        scatter(SPT, depth_SPT*0.3048, 'Marker', 'o', 'MarkerEdgeColor', 'k',
'MarkerFaceColor', 'k');
        SPTs = max(SPT);
        nice_max_SPT = nice_numbers(find(nice_numbers >= max(SPTs), 1));
        xlim([0, nice_max_SPT + 0.1 * nice_max_SPT]);
    elseif i == 12
        scatter(R, depth_SPT*0.3048, 'Marker', 'o', 'MarkerEdgeColor', 'k',
'MarkerFaceColor', 'k');
        nice_max_SPT = nice_numbers(find(nice_numbers >= max(R), 1));
        xlim([0, 100]);
    end
    xlabel(strrep(param_titles{i}, ' ', sprintf('\n')), 'FontSize', 8);

    ylim([min(depth), max(depth)]);
    if i == 1
        ylabel('Depth (m)', 'FontSize', 8);
    else
        set(ax, 'YTickLabel', []);
    end
    set(ax, 'XAxisLocation', 'top', 'YDir', 'reverse');
    grid on;

    if i < 12
        half_max_param_value = nice_max_param_value * 0.5;
        xticks([0, half_max_param_value, nice_max_param_value]);
        xtickangle(90);
    elseif i == 12
        xticks([0, 50, 100]);
        xtickangle(90);
    end
end

% Add the title above the subplots using annotation
annotation('textbox', [0 0.95 1 0.05], 'String', 'MWD - Bridgewater NH - B01
- Drilling', ...
    'EdgeColor', 'none', 'HorizontalAlignment', 'center', 'FontSize', 10);

filename = 'SiteName_BoreholeID_Drilling_SI.png';

% Save the figure as a PNG in high quality
saveas(gcf, filename, 'png');
```

APPENDIX C. ADDITIONAL MWD PROFILES WHILE DRILLING

C.1. MWD profiles collected while drilling in Loudon, NH

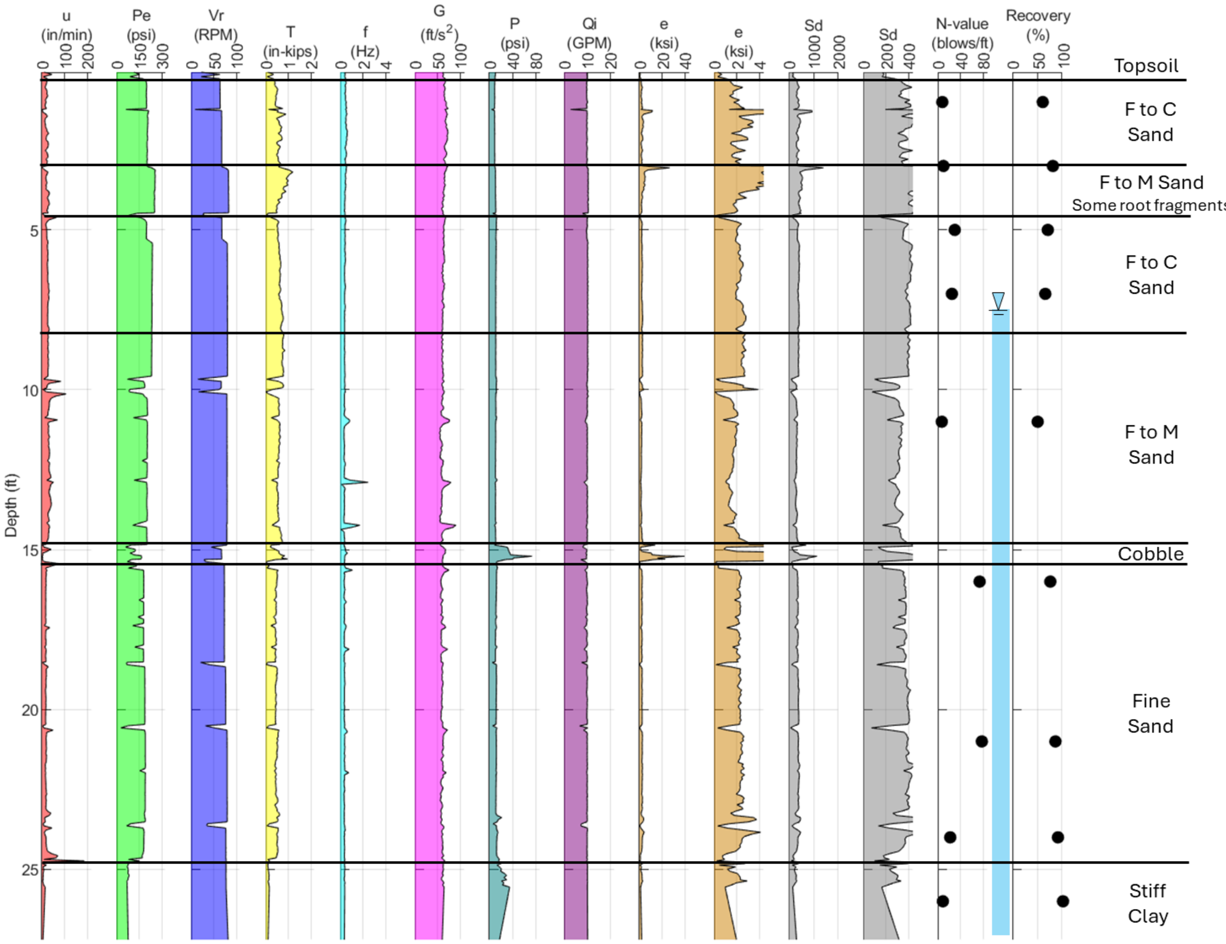


Legend:

u	Penetration rate	P	Mud pressure
Pe	Downthrust pressure	Vr	Rotation rate
Qi	Mud flow	e	Drilling energy
T	Torque	Sd	Somerton Index
f	Frequency	Qt	CPTu corrected tip pressure
G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.1. Profile B16 – Drilling and SPT – Loudon, NH.

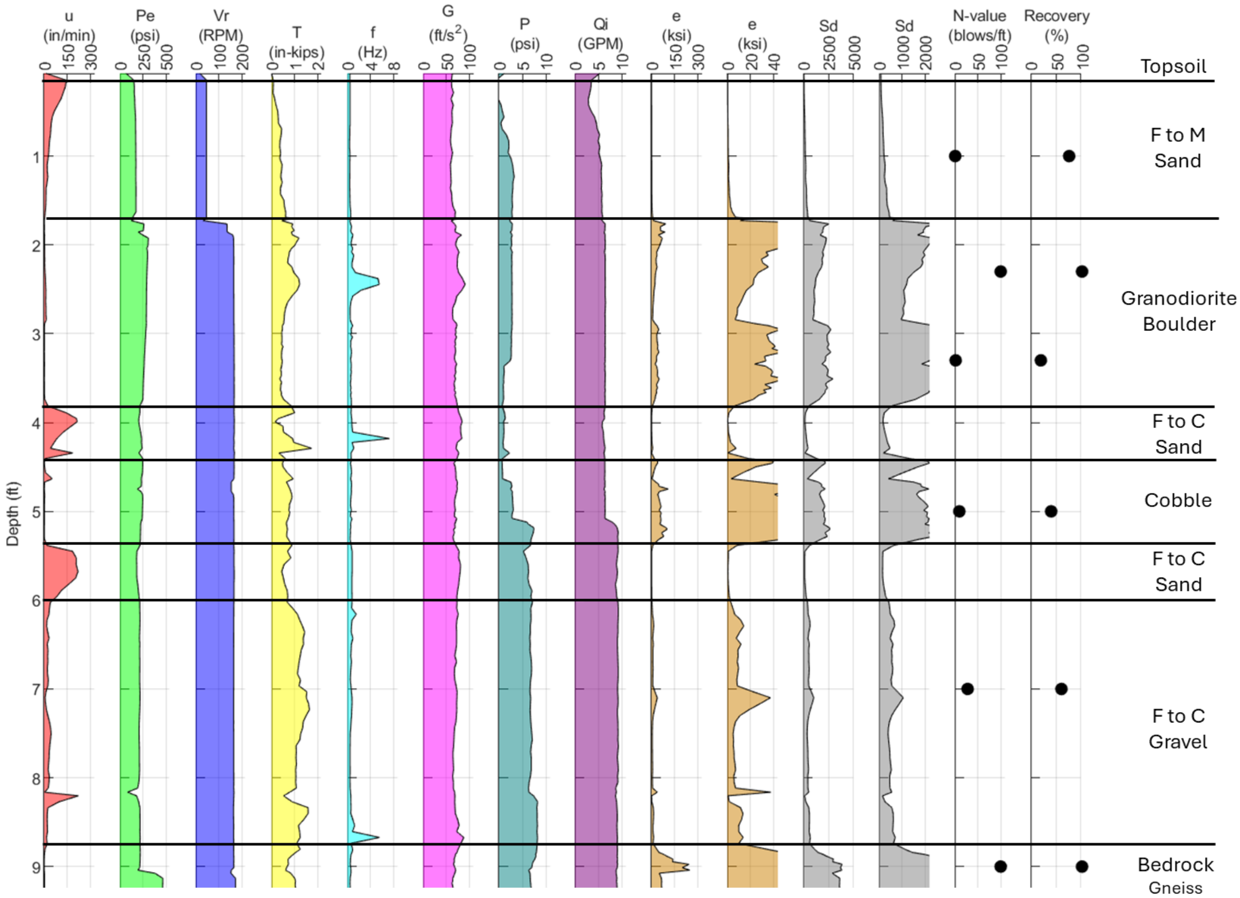
C.2. MWD profiles collected while drilling in Seabrook, NH



Legend: u	Penetration rate	P	Mud pressure
Pe	Downthrust pressure	Vr	Rotation rate
Qi	Mud flow	e	Drilling energy
T	Torque	Sd	Somerton Index
f	Frequency	Qt	CPTu corrected tip pressure
G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.2. Profile B01 – Drilling and SPT – Seabrook, NH.

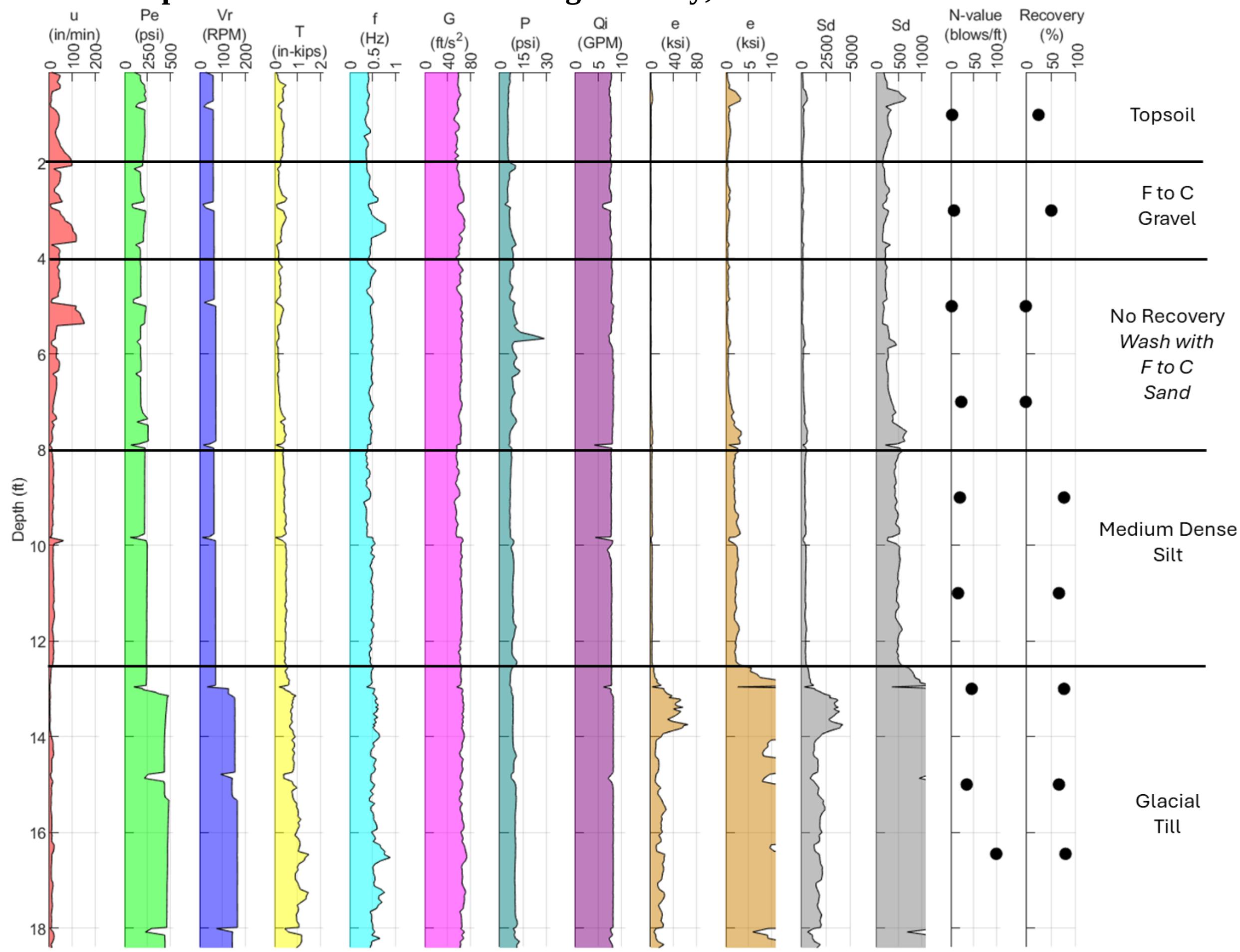
C.3. MWD profiles collected while drilling in Bridgewater, NH



Legend:				
	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.3. Profile B01 – Drilling and SPT – Bridgewater, NH.

C.4. MWD profiles collected while drilling in Derry, NH

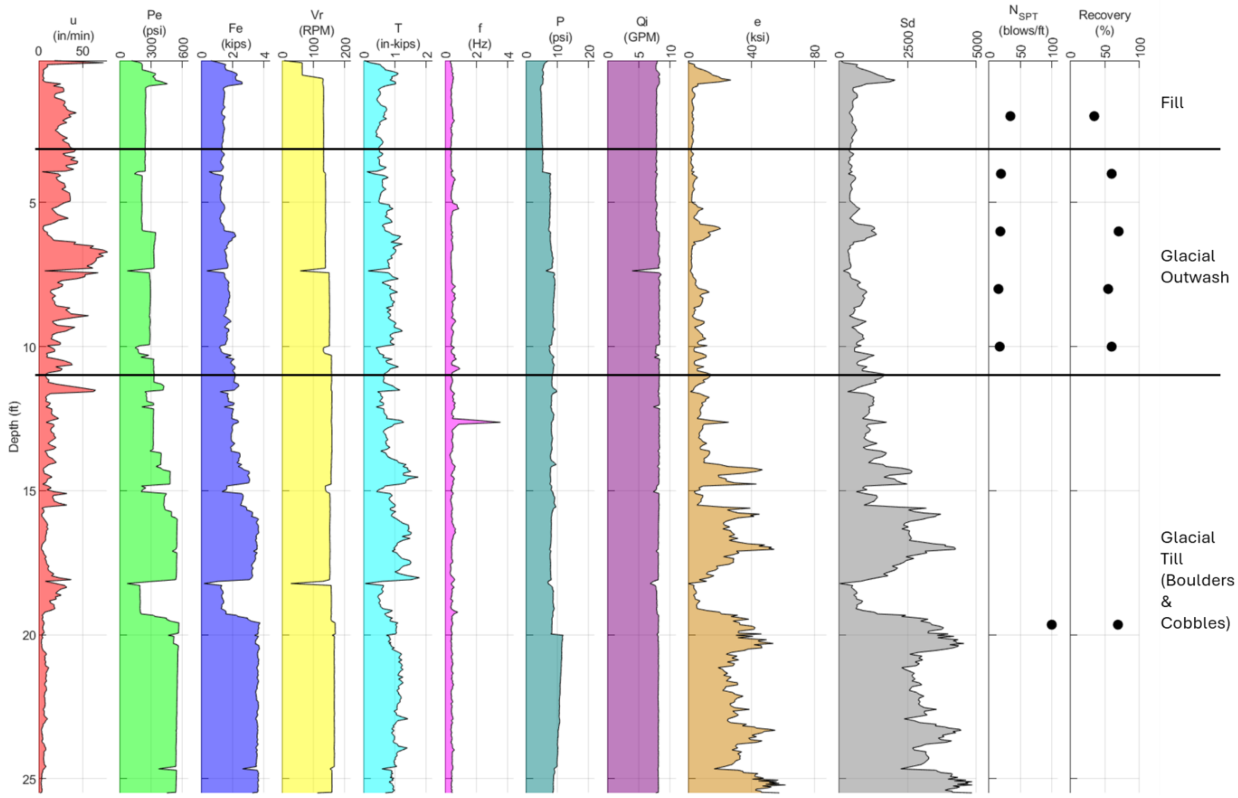


Legend:

u	Penetration rate	P	Mud pressure
Pe	Downthrust pressure	Vr	Rotation rate
Qi	Mud flow	e	Drilling energy
T	Torque	Sd	Somerton Index
f	Frequency	Qt	CPTu corrected tip pressure
G	Acceleration	fs	CPTu corrected sleeve pressure

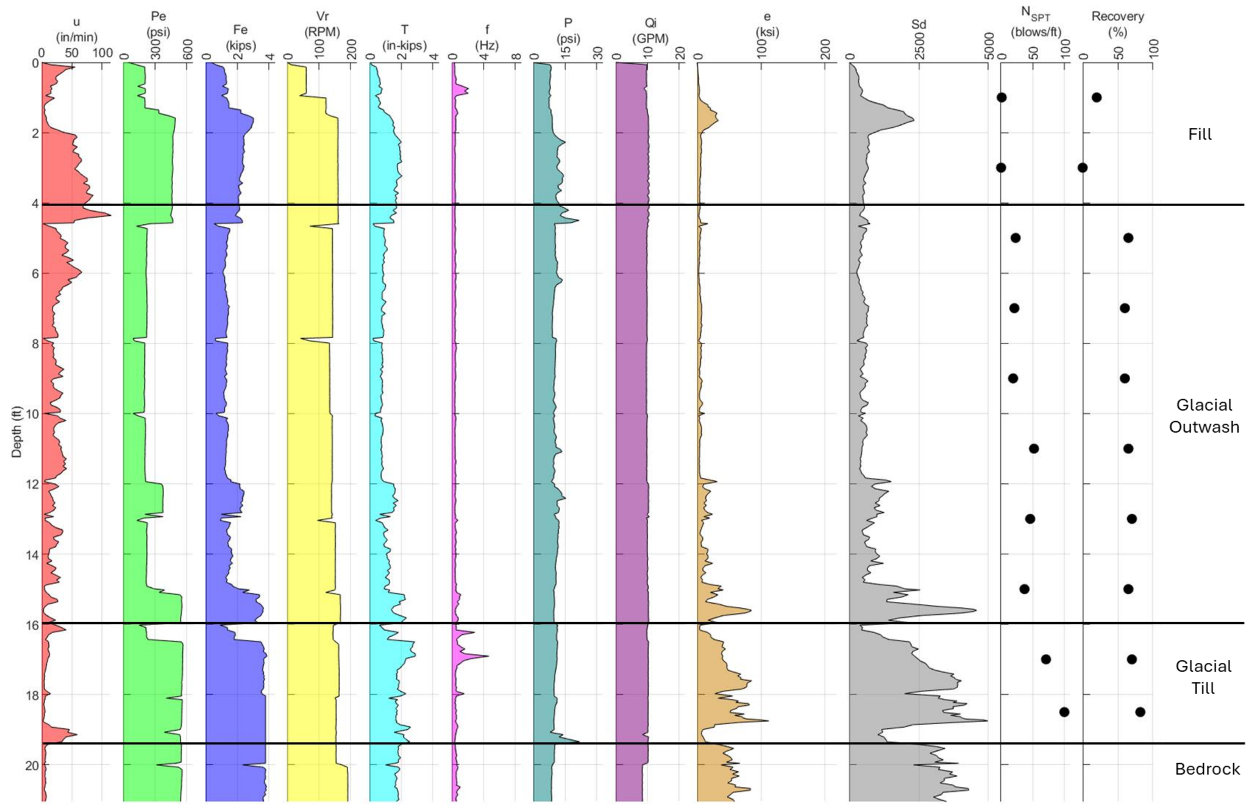
Figure C.4. Profile B01 – Drilling and SPT – Derry, NH.

C.5. MWD profiles collected while drilling in Londonderry, NH



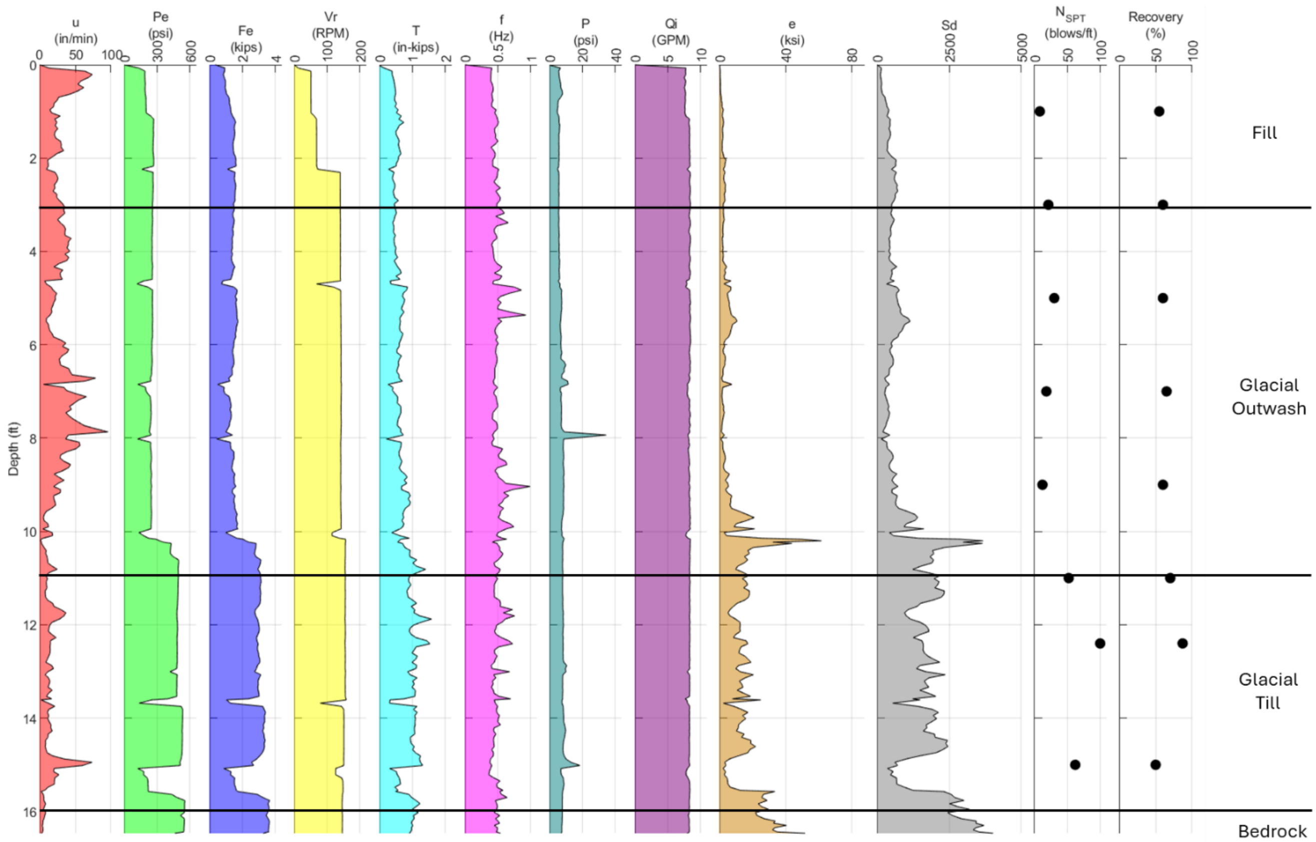
Legend:	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.5. Profile B01 – Drilling and SPT – Londonderry, NH.



Legend: u	Penetration rate	P	Mud pressure
Pe	Downthrust pressure	Vr	Rotation rate
Qi	Mud flow	e	Drilling energy
T	Torque	Sd	Somerton Index
f	Frequency	Qt	CPTu corrected tip pressure
G	Acceleration	fs	CPTu corrected sleeve pressure

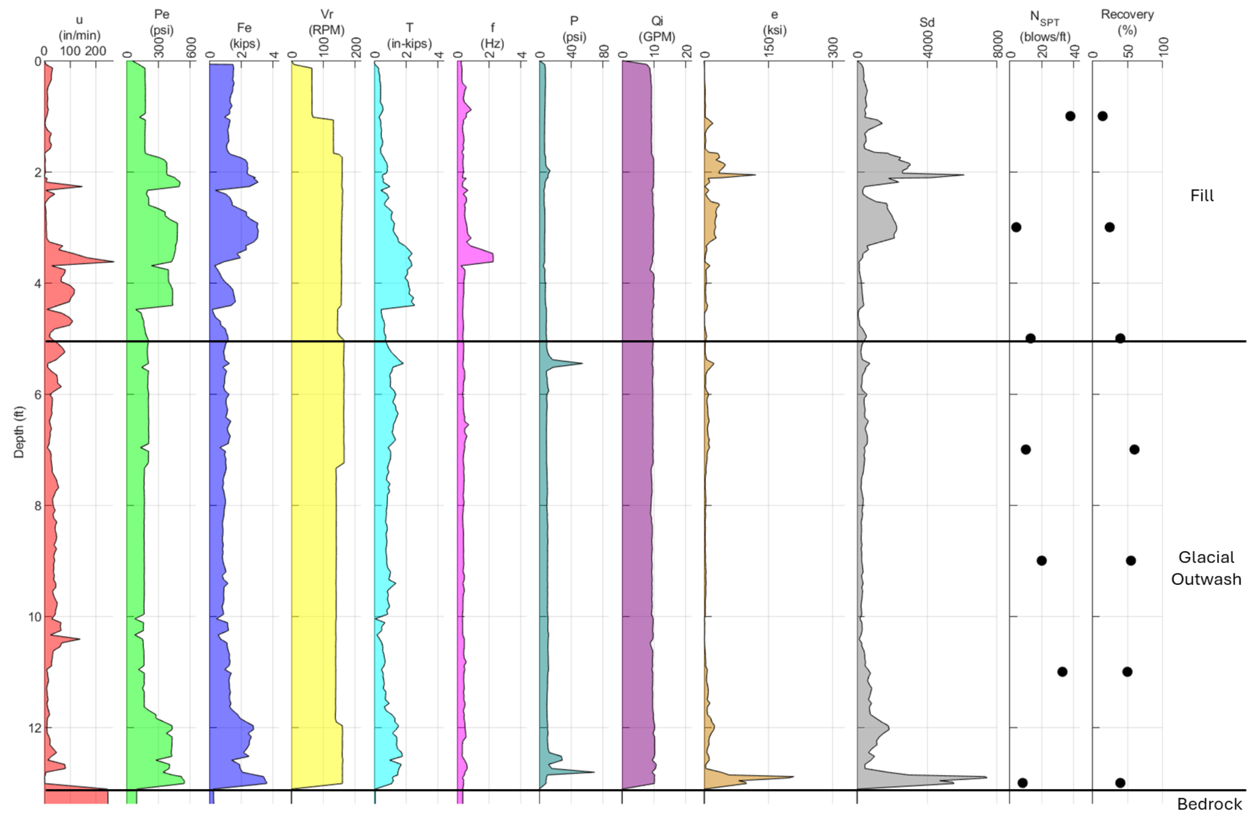
Figure C.6. Profile B08 – Drilling and SPT – Londonderry, NH.



Legend:

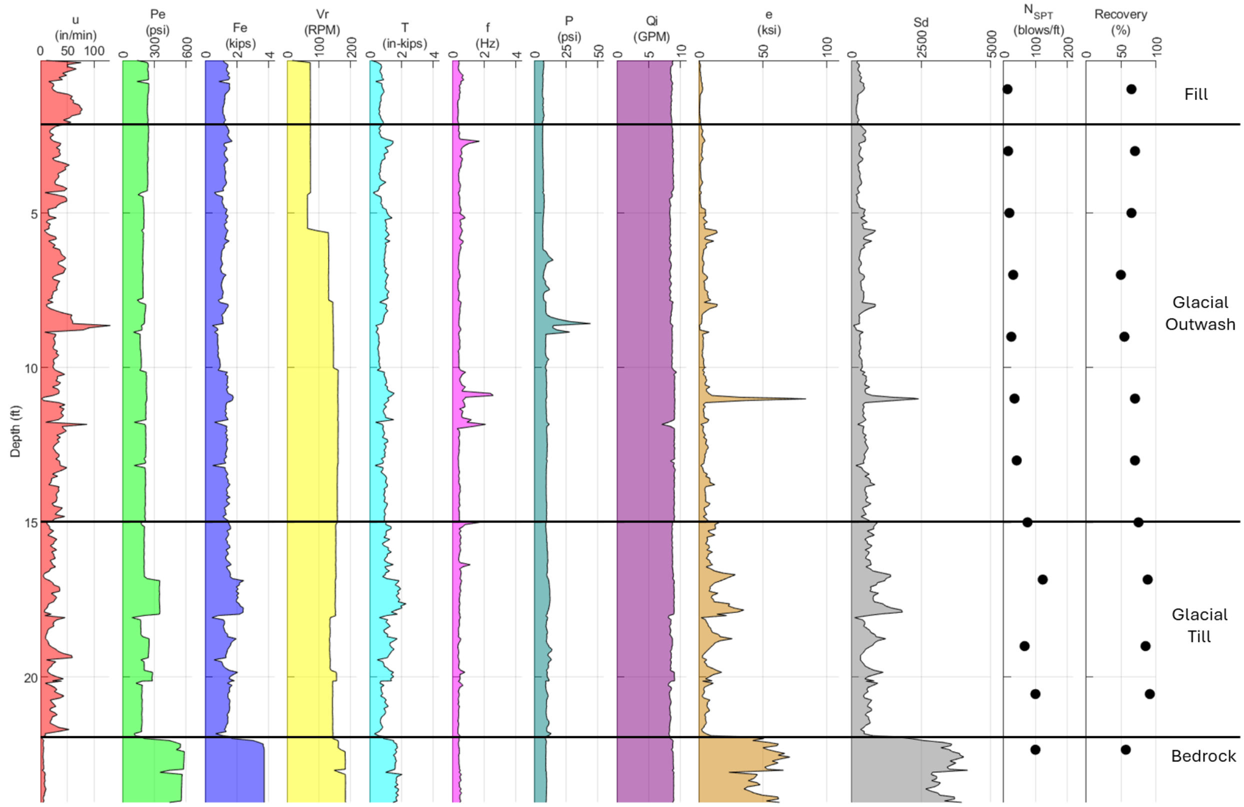
u	Penetration rate	P	Mud pressure
Pe	Downthrust pressure	Vr	Rotation rate
Qi	Mud flow	e	Drilling energy
T	Torque	Sd	Somerton Index
f	Frequency	Qt	CPTu corrected tip pressure
G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.7. Profile B09 – Drilling and SPT – Londonderry, NH.



Legend:				
	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

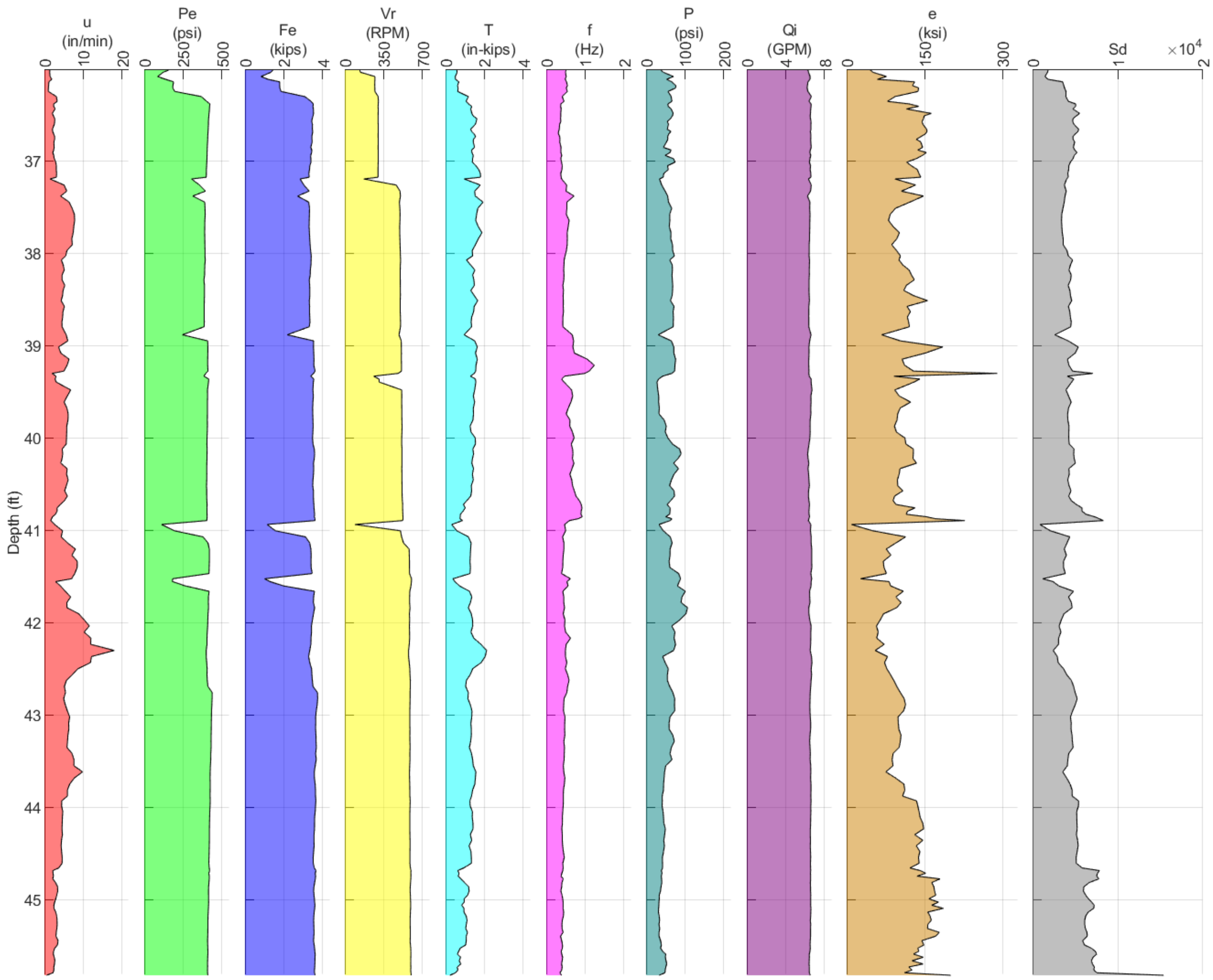
Figure C.8. Profile B10 – Drilling and SPT – Londonderry, NH.



Legend:

u	Penetration rate	P	Mud pressure
Pe	Downthrust pressure	Vr	Rotation rate
Qi	Mud flow	e	Drilling energy
T	Torque	Sd	Somerton Index
f	Frequency	Qt	CPTu corrected tip pressure
G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.9. Profile B13 – Drilling and SPT – Londonderry, NH.



Legend:

u	Penetration rate	P	Mud pressure
Pe	Downthrust pressure	Vr	Rotation rate
Qi	Mud flow	e	Drilling energy
T	Torque	Sd	Somerton Index
f	Frequency	Qt	CPTu corrected tip pressure
G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.10. MWD profile while coring – B02 – Londonderry, NH.

Figure C.11. B02 – Core and Recovery/RQD information – Run 1 (36 to 40.9 ft).

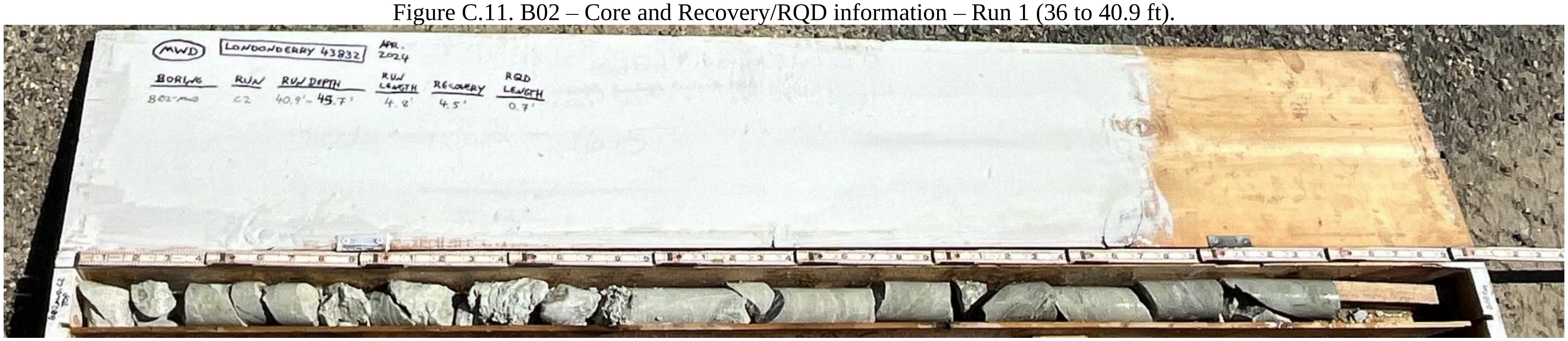
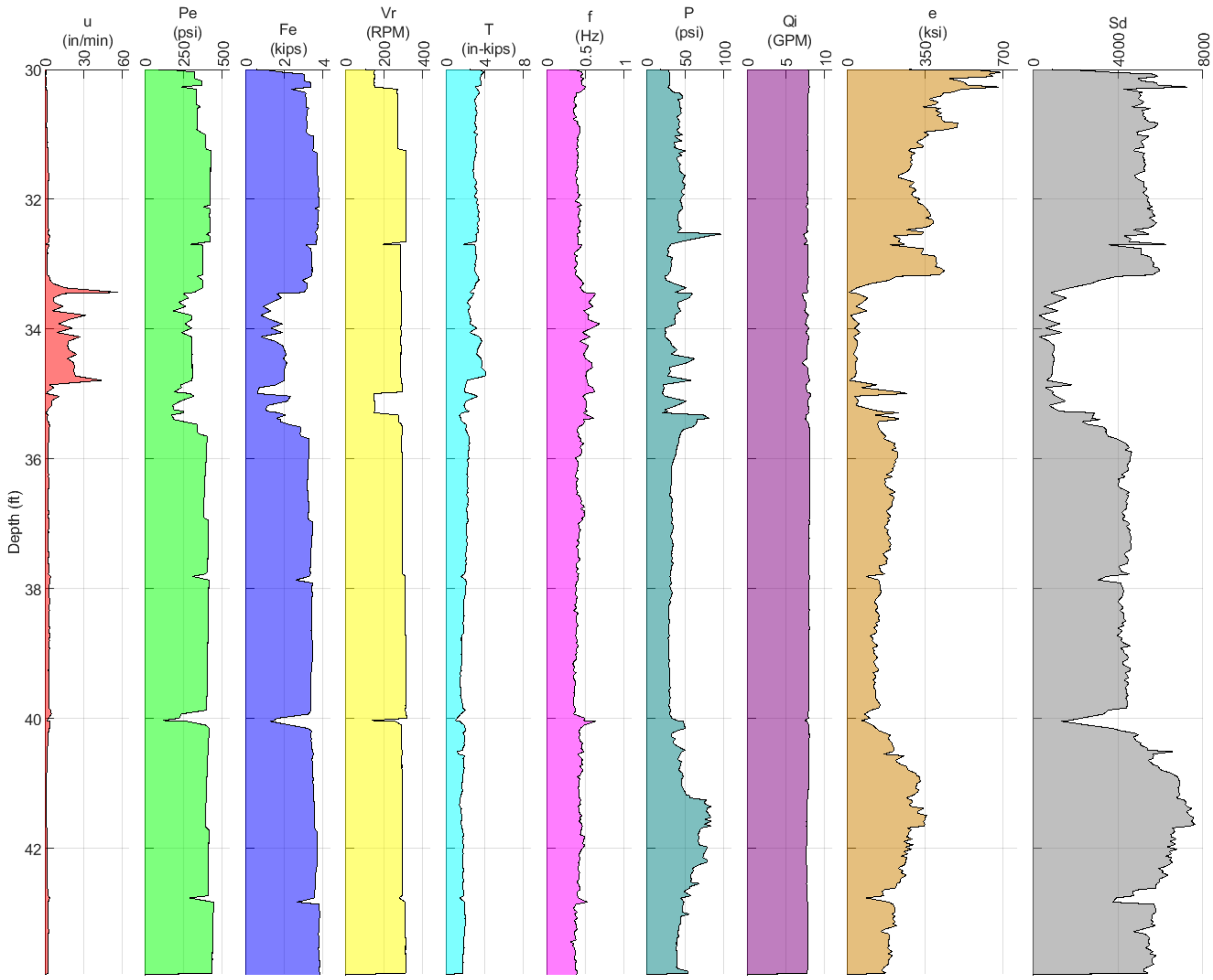


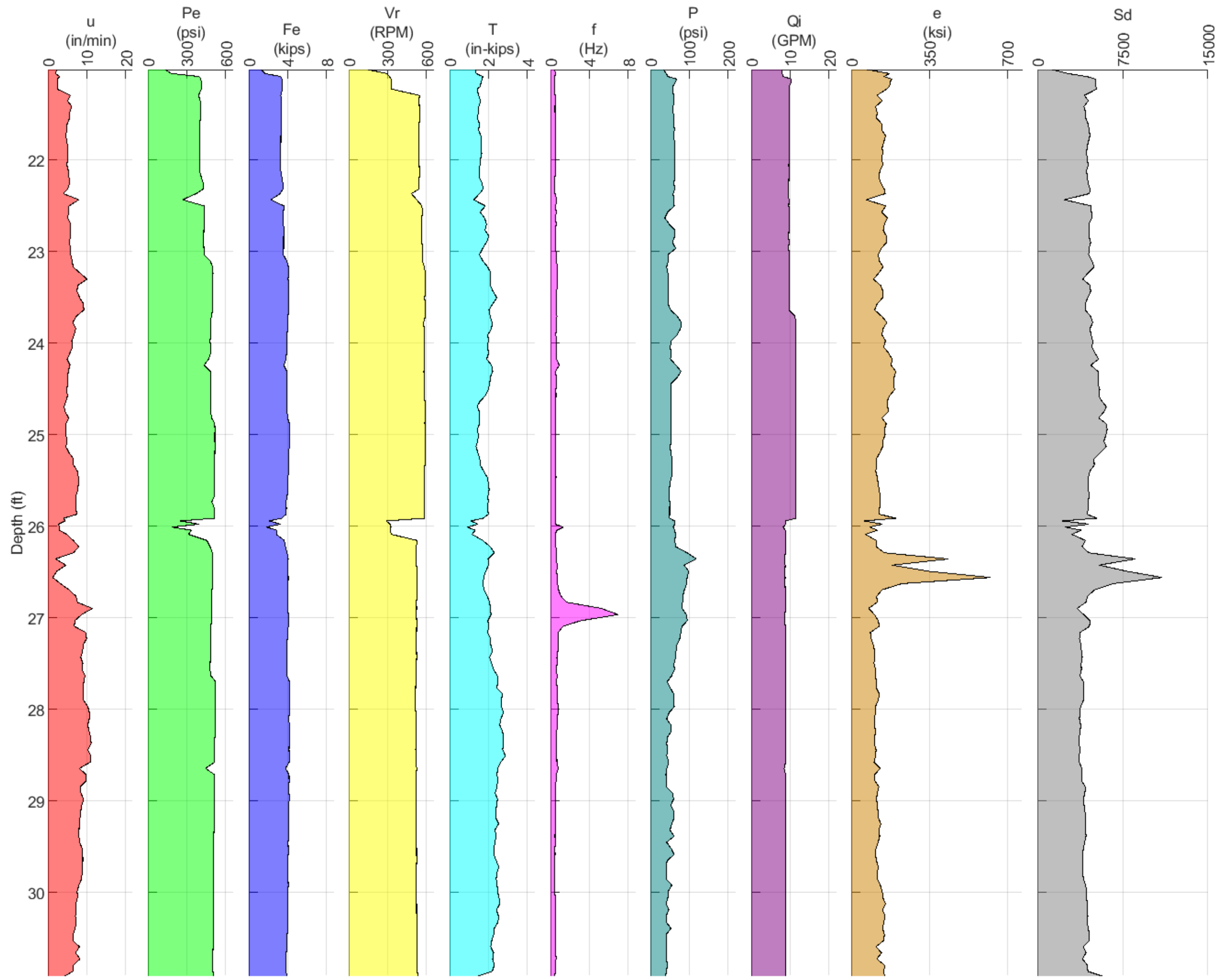
Figure C.12. B02 – Core and Recovery/RQD information – Run 2 (40.9 to 45.7 ft).



Legend:				
	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.13. MWD profile while coring – B05 – Londonderry, NH.

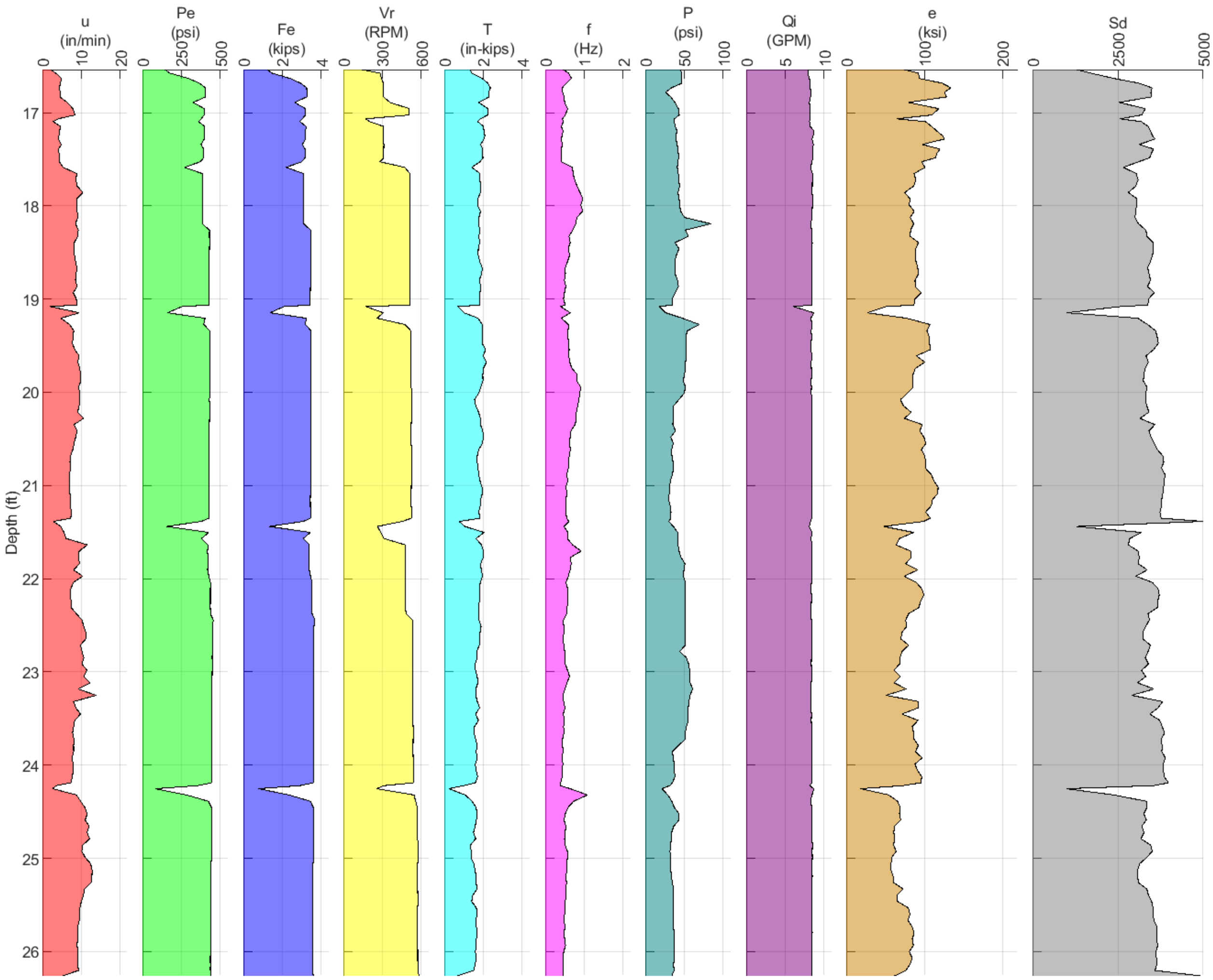
Figure C.14. B05 – Core and Recovery/RQD information.



Legend:	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.15. MWD profile while coring – B08 – Londonderry, NH.

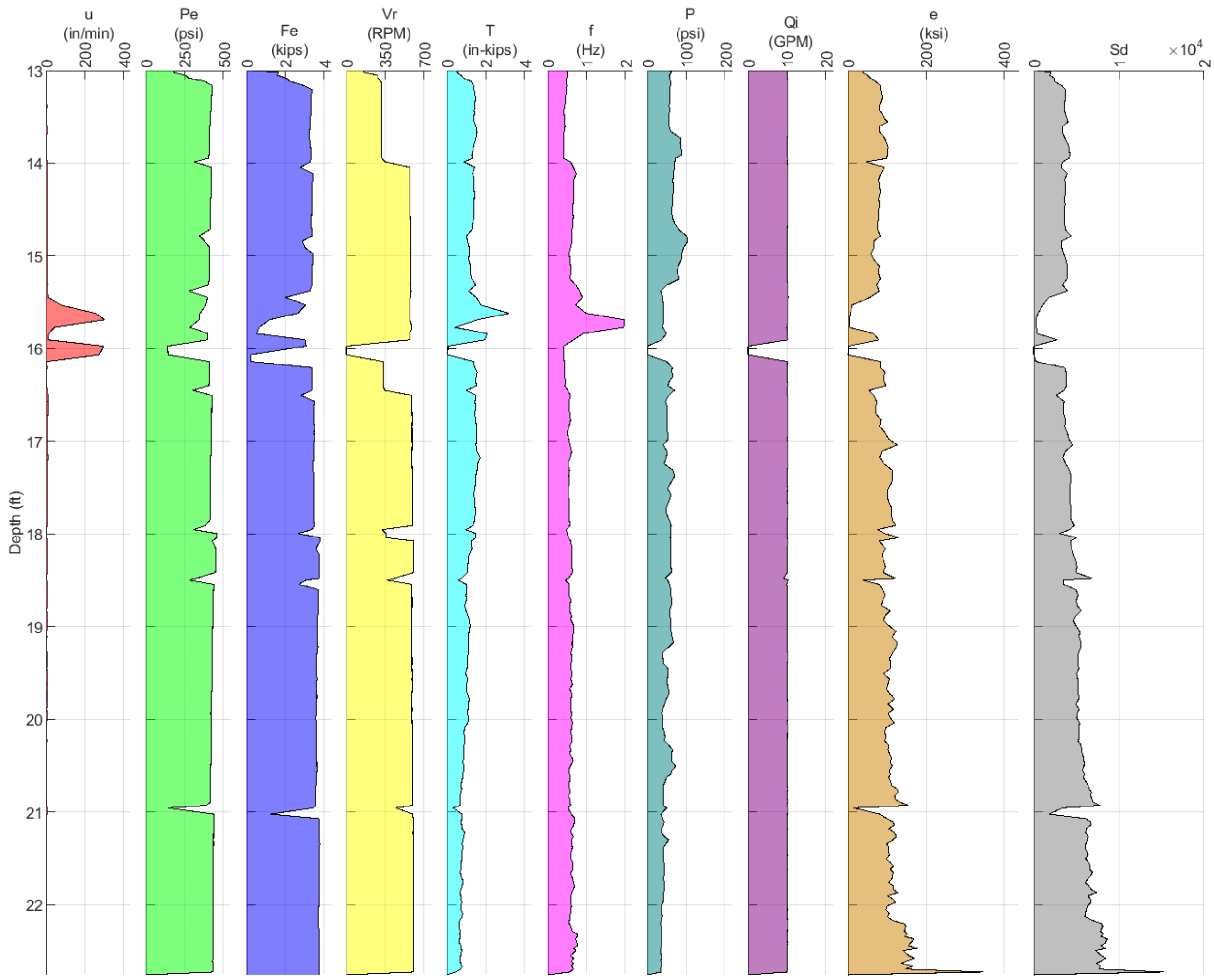
Figure C.16. B08 – Core and Recovery/RQD information.



Legend:	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.17. MWD profile while coring – B09 – Londonderry, NH.

Figure C.18. B09 – Core and Recovery/RQD information.



Legend:	u	Penetration rate	P	Mud pressure
	Pe	Downthrust pressure	Vr	Rotation rate
	Qi	Mud flow	e	Drilling energy
	T	Torque	Sd	Somerton Index
	f	Frequency	Qt	CPTu corrected tip pressure
	G	Acceleration	fs	CPTu corrected sleeve pressure

Figure C.19. MWD profile while coring – B10 – Londonderry, NH.

Figure C.20. B10 – Core and Recovery/RQD information.

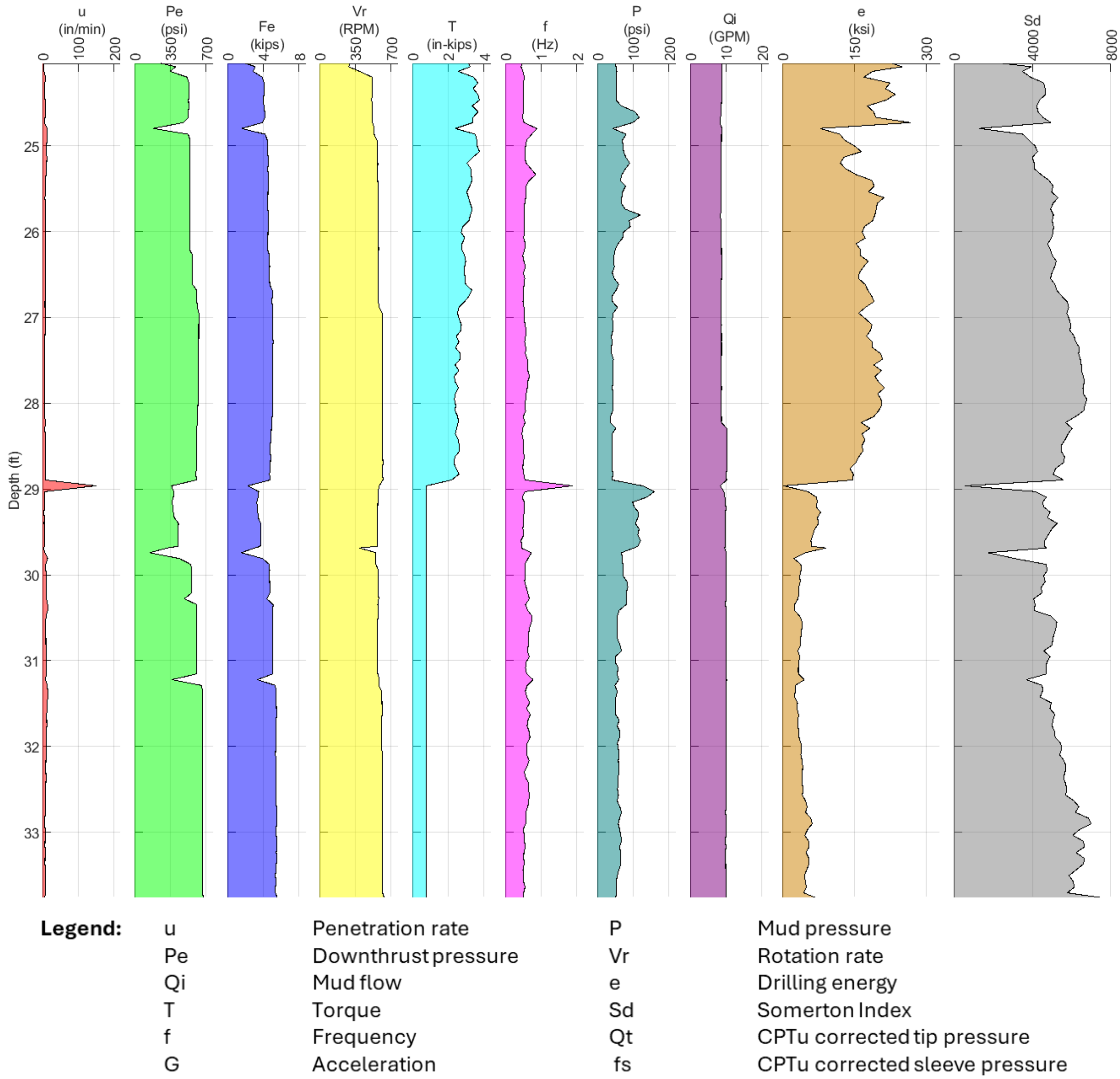


Figure C.21. MWD profile while coring – B13 – Londonderry, NH.

Figure C.22. B13 – Core and Recovery/RQD information.