Subsurface Characterization of Coastal Deposits Using Measurement While Drilling

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ABSTRACT

Measurement While Drilling (MWD) is a promising in situ test method that has gained increasing popularity in recent years. MWD can continuously characterize the subsurface while drilling any type of borehole in soil or rock without interfering with normal drilling operations. The latest MWD equipment gathers real-time data on numerous parameters that capture all aspects of the drilling process (e.g., depth, down thrust, rotation, torque, mud flow, and mud pressure). This paper summarizes MWD assessments performed in the coastal deposits of New Hampshire, USA. Profiles of individual and combined drilling parameters were used to differentiate between different soil layers and characterize subsurface conditions in complement with conventional, standardized geotechnical testing (e.g., SPT, CPTU) performed at adjacent boreholes. The results from this experimental campaign demonstrate the applicability of MWD systems to evaluate a broad range of geological conditions, from granular soils with erratic boulders to sensitive clays.

Keywords: Measurement While Drilling; MWD; Standard Penetration Test; Cone Penetration Test; Coastal Deposits

1. Introduction

Measurement While Drilling (MWD) is an in situ test where a drill rig is equipped with sensors that record all aspects of drilling (e.g., time, depth, rotation, down thrust, torque, drilling fluid pressure, and flow). As opposed to limitations imposed by conventional geotechnical test methods (e.g., Standard Penetration Test and Cone Penetration Test), MWD can be easily performed on any geological material (i.e., soil, rock, intermediate materials, and a mixture of soil and rock). Measurements are gathered in real-time and help improve drilling operations and obtain a rapid assessment of ground conditions, especially when a large quantity of time-consuming characterization profiles cannot be obtained due to time or budget constraints. MWD profiles are very useful to complement geotechnical investigations and continuously delineate the soil stratigraphy along a test site without interfering with normal drilling operations (Reiffsteck et al., 2018).

The latest Measurement While Drilling equipment, which includes the development of new sensor technologies to improve the accuracy of data collection, is now available from a number of suppliers. Recent advances include the development of wireless torque (or torque and thrust) sensors attached directly at the top of the drill string (Rodgers et al., 2018a; Rodgers et al., 2018b), as shown in Fig. 1. These new sensors address limitations from mechanical drill rigs used especially in the United States, which require a separate transducer to measure the torque since torque is not applied hydraulically like most rigs in operation outside the USA.

The initial uses of the technology in geotechnical applications were mostly addressed to the assessment of bedrock, in which different relationships between measured parameters (compound parameters) describing the resistance of the material to drilling were developed as the technology started to emerge. Among these studies are included the research efforts performed by Somerton (1959), Teale (1965), Girard (1985), and Pfister (1985), whose developed relationships were used in the first MWD technical standards recently published in Europe (ISO 22476-15:2016). Currently, U.S. standards are also being developed for the diffusion of the technology among departments of transportation and contractors. Since its first standardization, interest in MWD has significantly increased, especially for subsurface characterization, including all geological materials.

Figure 1. MWD equipment operated by a driller in Newington, NH. The yellow circle highlights the wireless torque sensor installed directly at the top of the drill string.

Although different studies have been performed on rock, there is still a lack of MWD data in different soil types and comparison 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).

Currently, conventional geotechnical testing (e.g., SPT) is still required in at least one borehole to properly assess local geology. Then, based on a reference profile, changes in stratigraphy can be evaluated based on drilling parameters. A second approach to assess or confirm stratigraphy in MWD is to observe the cuttings that emerge from the borehole. Soil or rock cuttings can confirm differences in soil type along the profile. Changes in color and grain size can usually be visually detected, and changes in texture can indicate whether the material is sandy, clayey, or silty. However, the test operator should not completely rely on cuttings, especially in uncased deep boreholes, where part of the cuttings emerging at the surface may originate from depths above the current drilling depth.

Given the existing gap in MWD data interpretation for soil profiles, this paper includes results from two experimental campaigns conducted in the coastal deposits of New Hampshire, USA. Despite their proximity (approximately 10 km between both sites), subsurface conditions varied significantly across testing sites, encompassing a wide range of geological materials from thick layers of sensitive clay to heterogeneous glacial deposits with erratic boulders. The MWD profiles were compared to SPT and CPT tests performed at adjacent boreholes.

2. Methodology

2.1. MWD equipment used

Fig. 2 presents the current MWD setup for the New Hampshire Department of Transportation (NHDOT) system. The sensors are connected to a junction box (Fig. 2a), whose output data is relayed to a data logger (Fig. 2b), which consists of a tablet where the data is displayed, and MWD settings and calibrations are performed. Data recording can be easily started or paused directly on the tablet or using the driller’s button (Fig. 2c).

Figure 2. Measurement While Drilling equipment at the New Hampshire Department of Transportation, USA.

The measurements from each sensor are performed automatically at a predefined interval of 5 mm, and data files can be exported through USB. The recorded parameters include:

- Down thrust pressure (Fig. 2d)
- Water pressure (Fig. 2e)
- Direct down thrust force and torque (Fig. 2f) – only torque measurements were available when the data presented in this paper was collected
- Rotation rate (Fig. 2g)
- Water flow (Fig. 2h)
- Depth (Fig. 2i)

2.2. Field experimental campaign

The NHDOT performed two field investigation campaigns between July and September of 2023. Tests were performed at the University of New Hampshire in Durham and near the Piscataqua River in Newington. Both sites are apart by 10 km, as shown in Fig. 3.

Figure 3. Location of test sites in Strafford County, NH.

The MWD boreholes were drilled with a 70-mm diameter tricone carbide roller bit, shown in Fig. 4. The tests in Durham started with a new bit (Fig. 4a), and the same bit was used in Newington. Fig. 4b shows that there was no wear in the drill bit at the end of both experimental campaigns, suggesting that the selected material may be a recommended option for collecting MWD profiles along soils despite the occurrence of boulders. The drilling fluid in all tests was water.

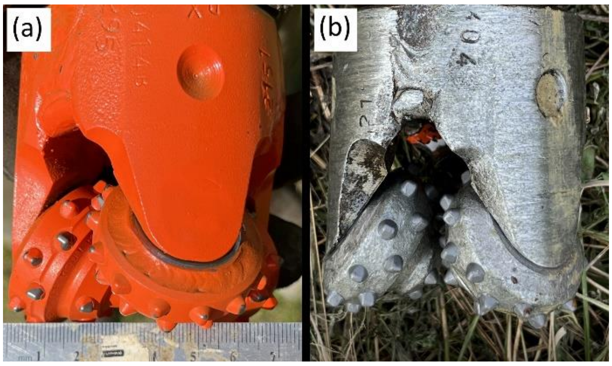

Figure 4. 70-mm diameter tricone carbide drill bit used in the experimental campaigns (a) before and (b) after tests – no significant wear.

2.2.1. Durham, NH, USA

The local geology includes a combination of artificial fill and poorly to well-graded till ranging from clay-size particles to large boulders, with small irregular layers of stratified sand and gravel (Koteff et al., 1989)over diorite bedrock. The borehole locations in Durham are presented in Fig. 5. All MWD boreholes were drilled uncased. A total of 4 MWD and 2 SPT profiles were obtained down to bedrock. Continuous SPT testing was performed following guidelines by ASTM D1586-18.

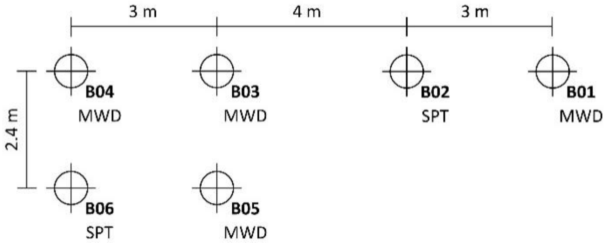

Figure 5. Site plan in Durham, NH.

2.2.2. Newington, NH, USA

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 20 m, followed by glacial till and basalt bedrock.

An initial SPT performed by the NHDOT in 2011 about 30 m from the test site identified a stratigraphy formed by fill, organic deposits, marine clay, glacial deposits (outwash and till), and bedrock (basalt). Fig. 6 presents the borehole locations at the Newington site, including the SPT test performed by the NHDOT in 2011 (B04). A CPTu profile was obtained following ASTM D441-16. B01 and B02 were drilled uncased down to bedrock.

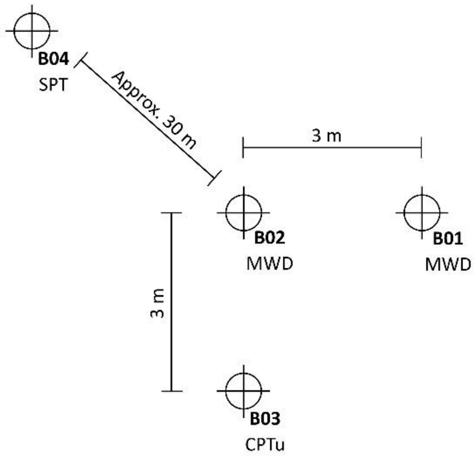

Figure 6. Site plan in Newington, NH.

Given the significant depth of the boreholes (up to 30 m), an attempt was made to drill additional boreholes with casing to improve the quality of the cuttings emerging at the surface. However, fine sand in the subsurface led the casing to unread in all three attempts.

2.3. MWD data processing

During all MWD operations, the driller tried to maintain the following parameters constant:

- Down thrust pressure
- Rotation rate
- Water flow

These parameters were maintained constant at each profile except when required by ground conditions (e.g., drilling through harder material, pressure build-up while drilling in clayey soils). Thus, changes in the remaining parameters (i.e., advance rate, water pressure, torque, frequency) were high indicators of changes in soil stratigraphy.

Although changes in subsurface conditions can be readily identified through changes in measured drilling parameters, a direct comparison between drilling parameters is insufficient to evaluate the stratigraphy. The complexity of these comparisons is even higher for multiple boreholes and/or different drillers. To address these limitations, the MWD standards recommend using compound parameters to normalize the test output. Compound parameters combine individual parameters into expressions of empirical indices or energies reflecting the resistance of the geological material to drilling (Somerton, 1959; Teale, 1965; Girard, 1985; Pfister, 1985). Higher calculated values indicate materials that are more difficult to advance a borehole. Analogously, lower values indicate softer materials that impose less resistance to drilling.

In this paper, two compound parameters were calculated for each profile: Somerton Index (S_D – Eq. 1), specific drilling energy (SDE – Eq. 2).

$$S_D = P_E * (V_R/V_A)^{0.5} \tag{1}$$

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

Where P_E = down thrust pressure (MPa)
V_R = rotation rate (rpm)
A = drill bit area (m²)
V_A = advance rate (m/s)
T = torque (MN.m)

3. Results

3.1. Durham, NH,

Figure 7 presents both SPT profiles obtained in Durham, NH. The heterogeneity of subsurface conditions is observed by comparing both profiles, which are only 7.4 m apart. 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 test at different moments to drill through with a roller bit, thus not allowing for data collection at these depths.

In glacial deposits such as those encountered in the Northeast U.S., blow counts are often erroneous since gravel or rock fragments can block the split-spoon, leading to high unreasonable N-values. In addition, 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 7-m profile to up to 8 hours.

Fig. 8 presents MWD results from borehole B03 in Durham/NH and the SPT results at corresponding depths. The soil profile from 0 to 6 m was obtained in 1h 20 min. When the rotation rate and thrust pressure are maintained approximately constant, changes in penetration rate usually reflect the resistance of the ground: higher penetration rates indicate softer materials, while lower rates indicate stiffer materials. A significant increase in drilling resistance can be observed in all compound parameters on harder ground (diorite boulder, glacial till, and bedrock). Sudden increases in frequency were also observed when drilling through gravelly soils, where the drill rig would also experience a higher vibration.

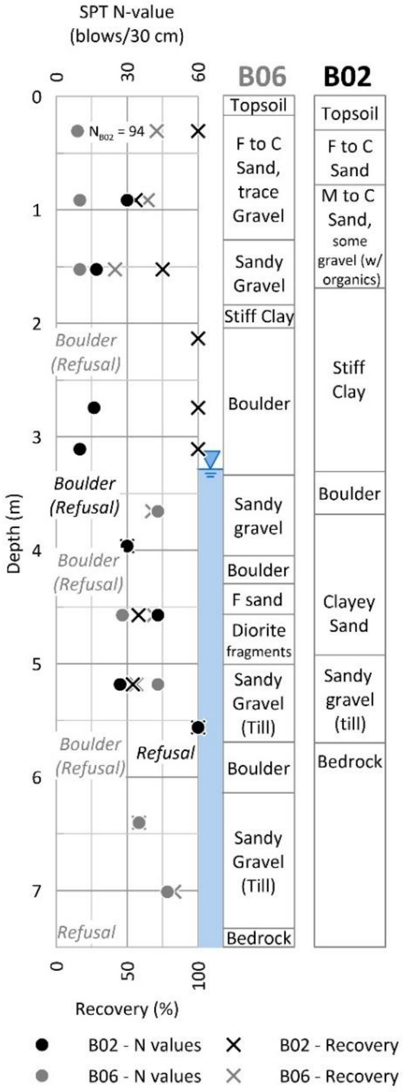

Figure 7. Location of test sites in Strafford County, NH.

A peak in water pressure was recorded above the water table level as the drill bit advanced through organic materials. The change from sandy to organic soil was visible through soil cuttings observed during the drilling process. The transition to the clayey layer experienced an increased drilling rate, an increase in torque, and a small decrease in all compound parameters. Despite being a cohesive soil, no variations in water pressure were recorded while drilling in the stiff clay – whose layer started immediately before the measured water table below 1.5 m.

Gravelly soils with boulders can then be detected below the clay layer as the compound parameters significantly increase and the drilling rate decreases to nearly zero at certain depth ranges. The depth interval corresponding to a very low drilling rate would correspond to the size of a boulder. In this profile, the encountered boulders were approximately 0.3 m deep.

The profile presented in Fig. 8 is an example of an MWD application where different types of geological materials can be evaluated in a single profile over a short period of time. Results from a second test, B05, are presented in Fig. 9. Similarly to B03, features such as changes in drilling rate, sudden changes in compound parameters, and rapid increase in vibrations can be used to delineate the soil stratigraphy in accordance with the observed soil cuttings.

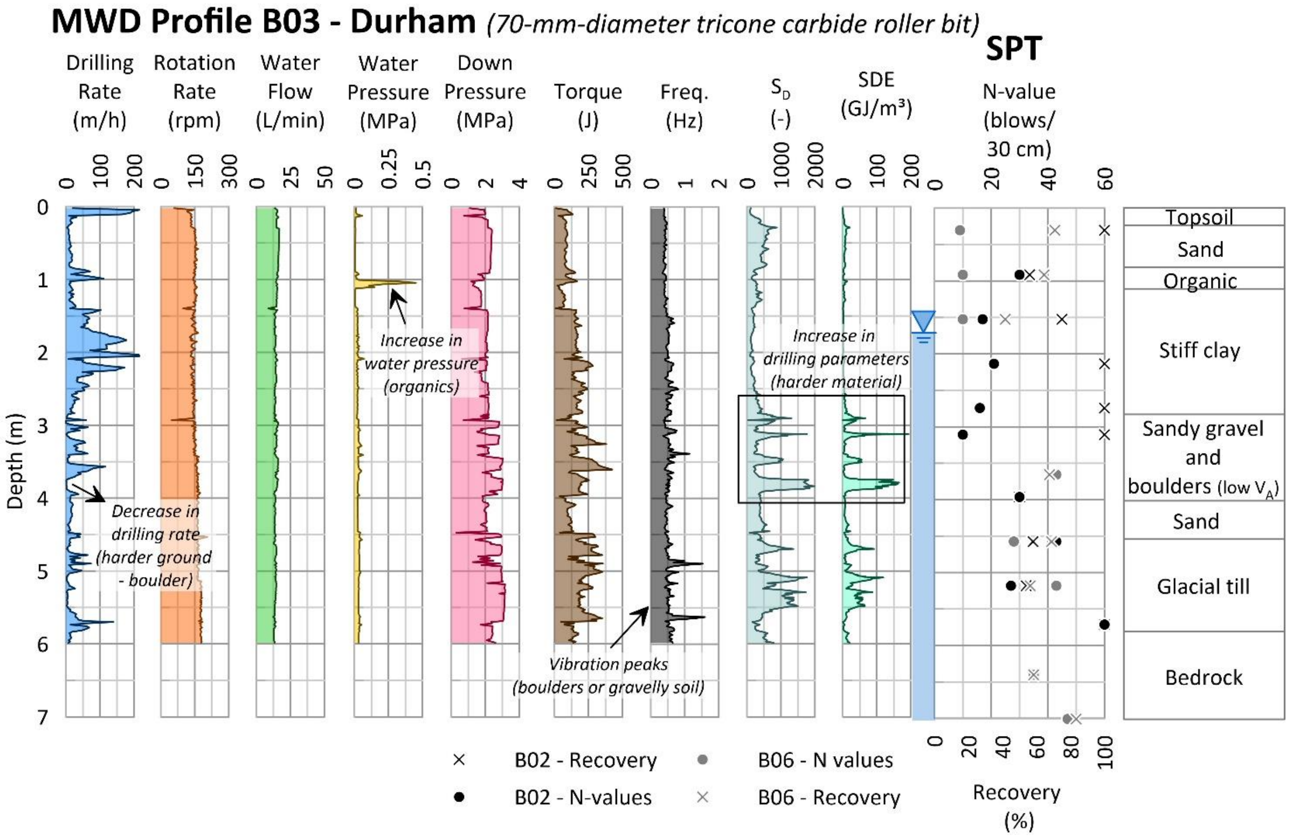

Figure 8. MWD profile B03 – Durham, NH.

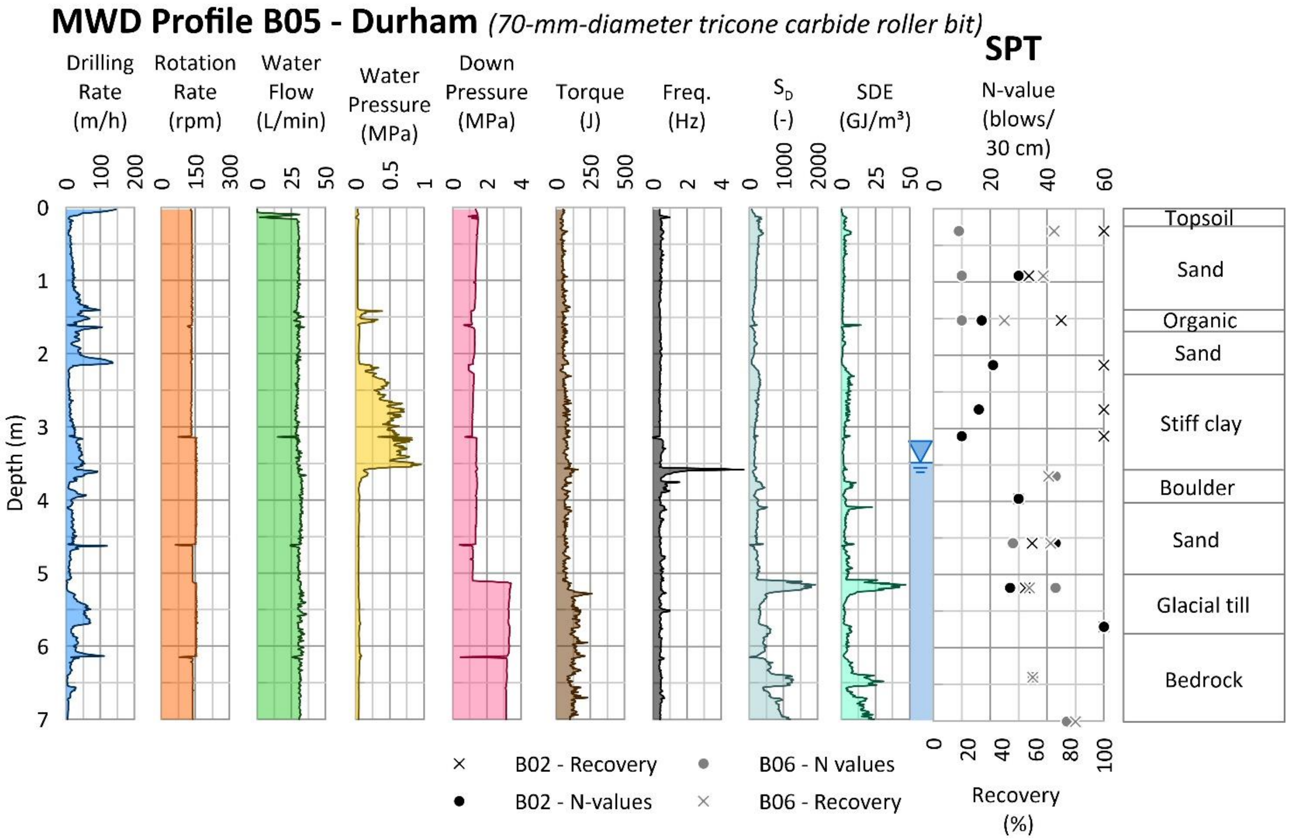

Figure 9. MWD profile B03 – Durham, NH.

However, while B03 experienced increased water pressure only while drilling through organic soils, a second, longer peak in water pressure was recorded for B05 while drilling on clay. Although the clays encountered along the SPT sampling for both profiles were similar,

The clay layer in B03 was situated within the water table, while the clay layer in B05 was detected above the water table. These results suggest that, for these site conditions, a pressure build-up has likely occurred due to drill bit clogging while drilling on unsaturated or partially unsaturated cohesive soil. In B05, the end of the clay layer is delineated by the end of the water pressure peak and the frequency peak at 3.5 m due to the presence of a boulder.

Fig. 10 summarizes the recorded N-values compared to the calculated SDE for each MWD profile. Due to the discretization of the SPT results at 0.6 m increments imposed by the method, a 0.6 m moving average was also calculated for the MWD results for direct comparison. It can be observed that an increase in N-values or SPT refusal usually accompanies an increase in material resistance (higher SDE values).

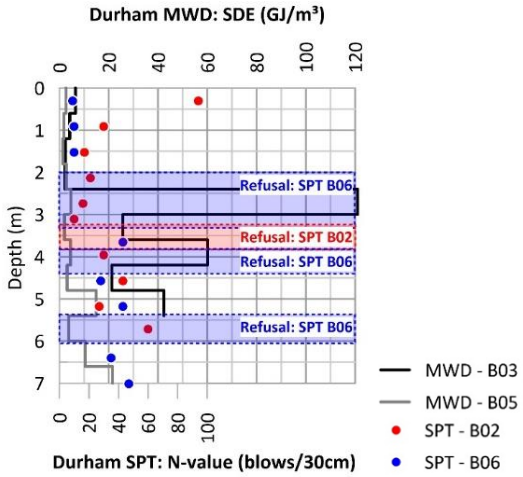

Figure 10. Comparison between SPT and MWD – Durham.

3.2. Newington, NH

MWD profiles up to 30 m in depth were obtained in Newington, including a variation of granular soils, organic materials, sensitive clays, and glacial till. The local stratigraphy is presented in Fig. 11 from SPT and CPTu results.

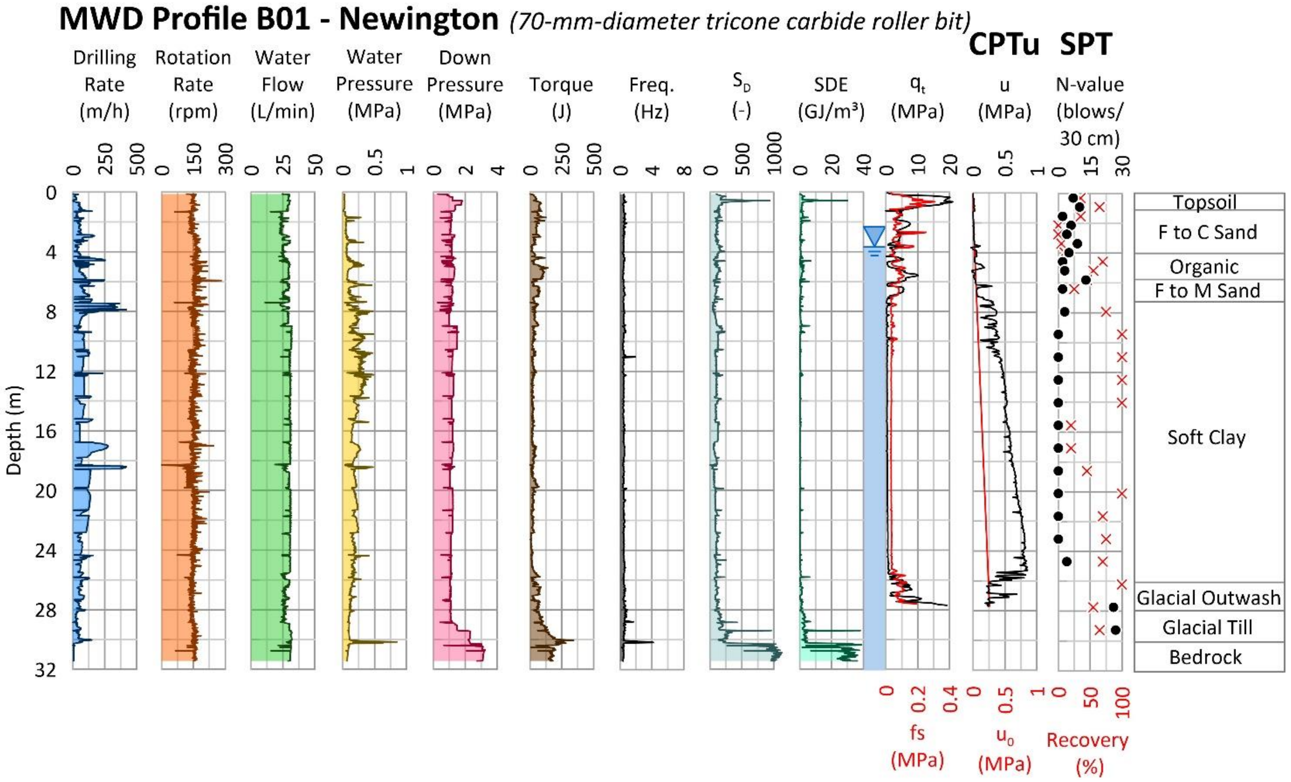

Figure 11. MWD B01 profile – Newington, NH.

Due to the low strength of the geological materials, the SPT blow counts did not provide detailed 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 sensitive clay layer. The presence of cohesive soil is confirmed by increased water pressure in addition to the hydrostatic pressure from groundwater. The depth correspondence between changes in ground resistance for both SPT and CPT tests suggests that the local stratigraphy is approximately similar.

Given the homogeneous site conditions across different boreholes, it was pertinent to assess the effect of rotation rate by decreasing the usual rotation rate from 150 RPM (measured at B01 – Fig. 11) to 60 RPM in one of the boreholes (B02 – Fig. 12).

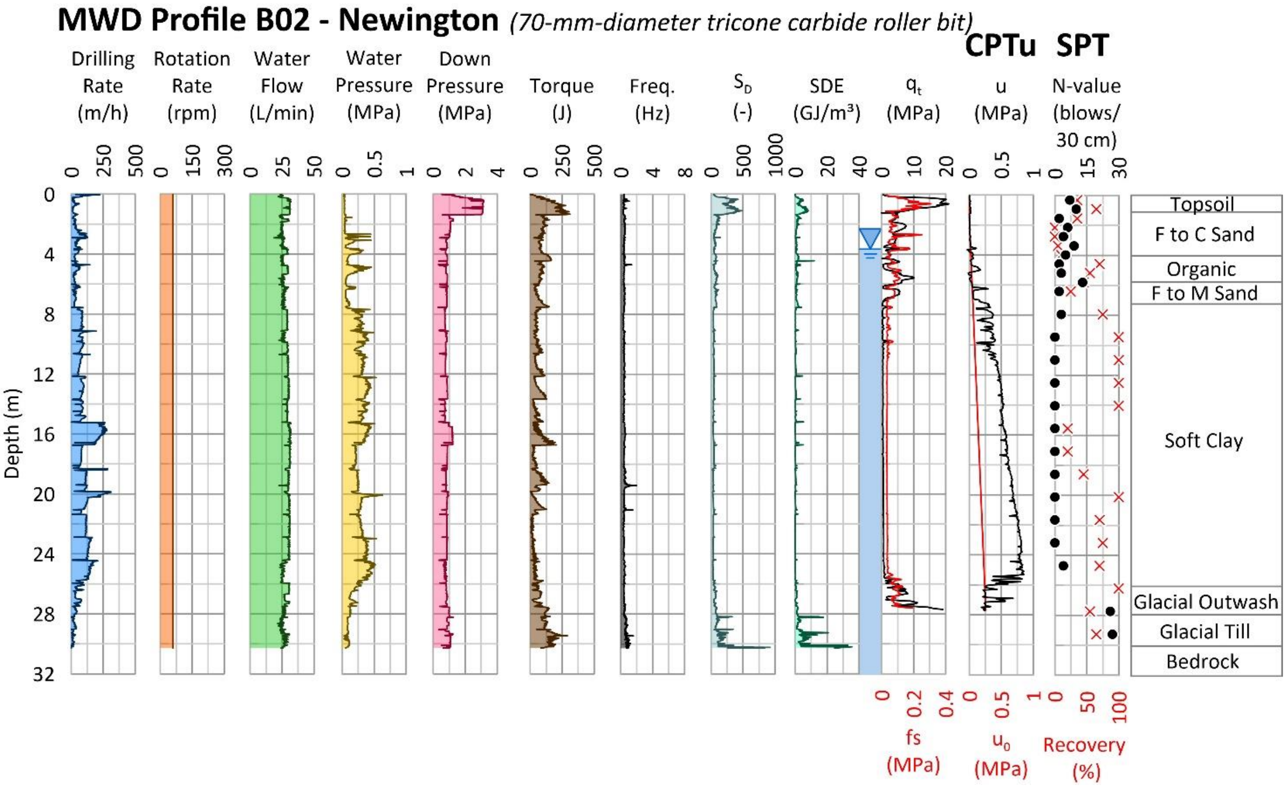

Figure 12. MWD B02 profile – Newington, NH.

In both MWD profiles, it is possible to observe a sudden increase in compound parameters as the thrust pressure needed to be increased to drill through glacial till and bedrock.

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 (Fig. 13). Each time a rod was added and drilling was resumed, the torque gradually increased until the next test interruption.

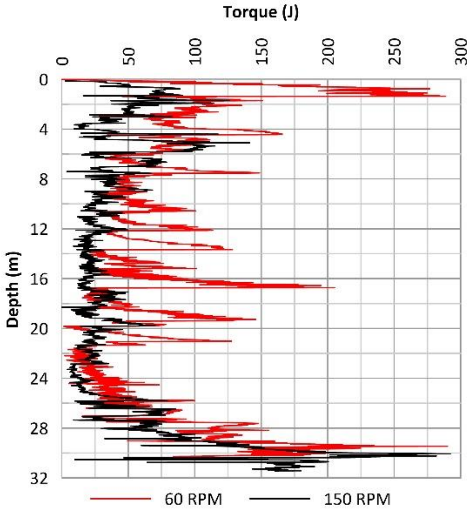

Figure 13. MWD torque comparisons – Newington, NH.

- A lower rotation rate led to lower penetration rates in materials that were not clay. The rotation did not seem to affect the advance drilling rate despite the recorded spikes in torque before adding rods at 60 RPM.
- Smaller rotation rates led to smaller compound parameter values, where slight variations in the calculated parameters along stratigraphy divisions are more noticeable.

Water pressure build-up was recorded similarly for both rotation rates. It is suggested that for these soil conditions, the driller likely used a low water flow, thus allowing for clogging in the drill bit as drilling advanced in the clay layer.

Direct comparisons between SPT and MWD and CPTu and MWD data are presented in Figs. 14 and 15, respectively.

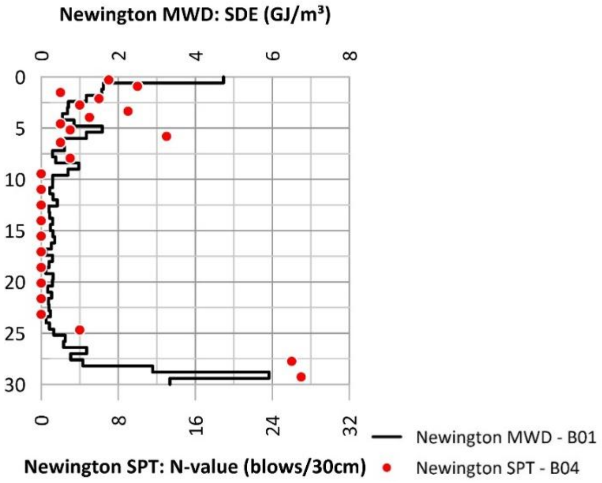

Figure 14. Comparison between SPT blowcounts and MWD results in Newington, NH.

The MWD data in each figure were plotted as moving averages compatible with the SPT and CPTu measurements. Therefore, in Fig. 14, a 30-cm moving average was calculated for the specific drilling energy. In Fig. 15, the MWD moving average was equal to 5 cm. It can be observed in both figures that the cone resistance and SPT blow counts follow similar trends as the MWD results at corresponding depths. That is, increases or decreases in calculated compound parameters for MWD were accompanied by similar trends for the SPT and CPTu tests. Such comparison illustrates the potential of MWD for subsurface characterization using a rapid test method that can be performed independently of local geology.

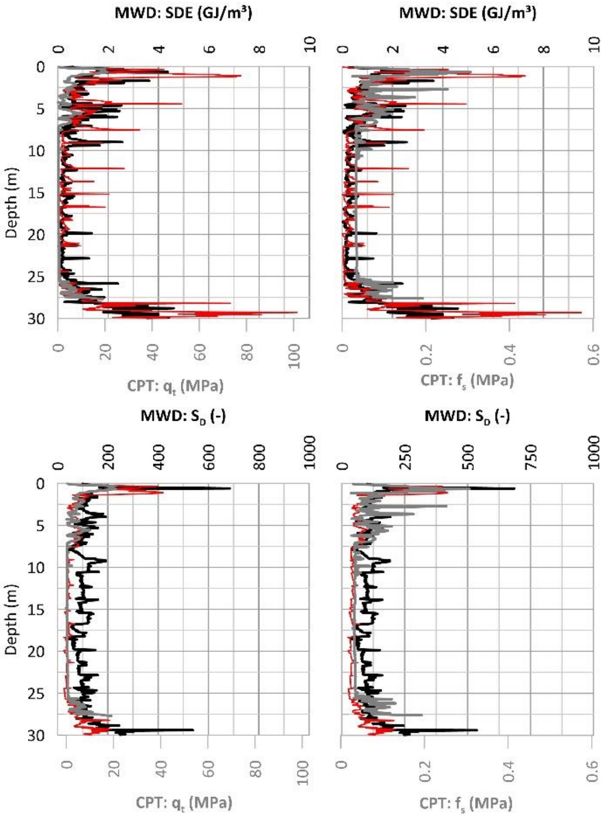

Figure 15. Comparison between MWD compound parameters and CPTu results in Newington, NH.

Conclusions

This paper presented MWD results from two sites encompassing a wide range of geological materials, from thick layers of sensitive clay to heterogeneous glacial deposits with erratic boulders. Results demonstrate the potential use of MWD systems to provide useful information on local geology from a simple, rapid test that does not affect drilling operations.

Profiles of individual and combined drilling parameters could be used to differentiate between different soil layers and characterize subsurface conditions in complement with conventional, standardized geotechnical testing (e.g., SPT, CPTU) performed at adjacent boreholes. In addition to its significant contribution to geotechnical subsurface characterization, the continuous MWD monitoring of drilling advancement could help evaluate geologic 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 need to be drilled through using a roller or core bit. In glacial deposits such as those encountered in the northeast U.S., blow counts were often unreliable when split-barrel samplers were blocked by gravel or rock fragments, leading to high unreasonable N-values.

Current research performed by the NHDOT includes the use of a new wireless sensor that, in addition to torque, also measures the down thrust force at the top of the drill string. These measurements should allow for more accurate calculations of compound parameters to assess ground conditions.

Additional observations regarding water pressure build-up in the presence of cohesive materials are required in future evaluations to better understand how to drill efficiently without creating excess fluid pressure such that MWD parameters can be used more reliably to define stratigraphic details.

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