Organization and Analysis of Measurement While Drilling (MWD) Data

Task 1 Report: Organization and Preprocessing of Collected Data

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Abbreviations

CME: Central Mine Equipment

CPT: Cone Penetration Test

DD: Dry Density

HSA: Hollow Stem Auger

MDT: Montana Department of Transportation

MWD: Measurement While Drilling

N1, N2, N3. N: SPT blow counts

PMT: Pressure Meter Test

REC: Sample Recovery

RQD: Rock Quality Designation

SPT: Standard Penetration Test

Su: Undrained Shear Strength-Total

Su_r: Undrained Shear Strength-Residual

UCS: Unconfined Compressive Strength

UW: Unit Weight

VST: Vane Shear Test

1. Background

This report comprises the Task 1 report as specified in *Section 4.3 – Task Reports* in the MDT executed contract.

The design and construction of any foundation, especially deep foundations in transportation infrastructure projects, requires reliable information about subsurface conditions.This usually includes not only information about the different soil/rock layers and their strength properties but also their variability across a project site. For example, Rodgers et al. (2018) reported that the stratigraphy and strength characteristics of the subsurface underneath two separate bridge piers at a project site varied significantly. Their study indicated that the mean unconfined compressive strengths (UCS) of the bearing material from two individual borings spaced only 5 meters (16.4 ft) apart at a drilled shaft site in Fort Lauderdale, Florida, were about 50 percent different. This example illustrates that it is critical to obtain accurate strength properties to reduce uncertainty in the design stage. Having a means of estimating the strength of subsurface geomaterials at every location and at every depth of interest in a project would be of high value. This is where estimating (correlating) the strength data from parameters that can be continuously measured during the drilling operation at a site would become extremely valuable.

1.1. Literature Review

Fortunately, Measurement While Drilling (MWD) technology has shown potential to improve the characterization of the variability of soil/rock layers and their strength characteristics. MWD has a half-century history of successful use for improving subsurface characterization in the natural resource industries (Somerton 1959; Teale 1965; Warren 1984; Segui and Higgins 2002; Smith 2002; Rai et al. 2016; Rickert 2017; Yang et al. 2020). Since the 1980s, MWD has been instrumental in developing directional drilling within the petroleum industry (Barr 1984; McKenney and Knoll 1989; Pittard et al. 1989). In the geotechnical engineering realm, however, MWD technology is still in early research stages (Bishara and McReynolds 1990; Schunnesson 1996; Gui et al. 2002; Sadkowski et al. 2010; Reiffsteck 2011; Laudanski et al. 2013; Lonstein et al. 2015; Zetterlund et al. 2017; Reiffsteck et al. 2018; Rodgers 2019; van Eldert et al. 2020; McVay and Rodgers 2020 Roye 2020). This is partly due to the different types of drilling and drill bit configurations used in energy resources industries compared to those used in the geotechnical industry. With few exceptions, the correlations developed between MWD parameters and rock strengths in the energy resources industry usually contain coefficients for specific bit configurations and drilling operations (Teale 1965; Warren 1984; Wolcott and Bordelon 1993; Karasawa et al. 2002b, 2002a; Detournay et al. 2008; Li and Itakura 2012) that are not applicable to geotechnical drilling practices, such as the use of auger bits, that are usually used in drilled shafts projects (Rodgers et al. 2018a). To further complicate the matter, according to Bingham (1964), there are about 26 parameters that could influence drilling and in turn, affect any correlation between MWD parameters and rock strength.

According to Karasawa et al. (2002a, 2002b), correlation developed between MWD parameters and rock strength could be different in soft, medium, and hard rocks, unless a universal correlation can be developed. This is true for geotechnical correlations as well and the correlations mentioned above are only derived based on soft (less than 800 psi) sedimentary rocks. Reiffsteck et al. (2018), also explain that the capability of each method to evaluate the geotechnical characteristics of subsurface layers depends on the geomaterial type and mechanical properties being evaluated. They further elaborate that the soil texture, including particle size, clay content,compactness, and moisture content could affect MWD data and therefore any derived correlations. They also emphasize that the type of drilling tool (bit) plays an important role in developing correlations between MWD parameters and geomaterial properties. They further added that a relationship normalized based on the energies used by different tools is not available yet, meaning that different correlations are still needed for each type of tool used.

One of the main goals of this study is to investigate data collected through the MWD program of MDT, develop correlations between measured data and strength of the soil/ rock layers commonly encountered in the state of Montana and finally evaluate the influence of different measured parameters on the correlations. The primary focus of this effort will be within sedimentary intermediate geomaterials (IGM's), such as sandstone, claystone, siltstone, and mudstone, which are prevalent throughout Montana, and which exhibit strength properties for both a stiff soil and a soft rock, making strength interpretation, subsurface modeling and design a challenge.

2. MWD Data Collection

Utilizing a $50,000 contract funded in early 2020 through FHWA's Every Day Counts (EDC) 5 Initiative, MDT installed a Jean-Lutz MWD system on their Central Mine Equipment (CME) 1050 ATM drill rig. Since then, MDT has been collecting MWD data on projects throughout the state. The standard set of collected data includes drilling depth, drilling rate, rotation speed, down pressure, hold-back pressure, mast vibration, flow rate, and fluid pressure. A mechanical torque sensor was not included with the standard Jean Lutz MWD system and was added to the drill rig by MDT personnel. MDT continues to collect MWD data in an attempt to improve collection of accurate mechanical torque data with their aftermarket torque sensor. It is worth mentioning that auxiliary data including standard penetration test (SPT), vane shear test (VST), cone penetration test (CPT), pressure meter test (PMT) as well as geophysical survey data, can also be collected and can be included in MDT's comprehensive database. Data were collected at MDT project sites to investigate proposed cuts, embankment fills, culverts, and bridge foundations. The challenges with MWD technology include a combination of organizing large amounts of collected data of various types and correlating these data to the desired subsurface soil and rock strength parameters. As with most 'real world' data, quality control of the raw data is imperative before attempting any statistical/correlation techniques.

The MDT began collecting MWD data in the summer of 2020 and additional data collection is ongoing. For this project, we used MWD data collected at a number of sites along an approximate 20-mile stretch of Highway 200 in the Glendive district of eastern Montana. Figure 1 is a map segment showing the site locations used for analysis. The near-surface geology in the project vicinity consisted of IGMs typical of eastern Montana.

Figure 1. Map segment showing location of MWD sites along Highway 200 used for analysis.

3. GIS Data Portal

The focus of Task 1 was the organization and preprocessing of collected MWD data. For this task, collected MWD data, as well as field VST, PMT, SPT, and laboratory UCS data, were organized and loaded into a GIS-based interactive map database. *Drill Data Maps* was hired as an outside consultant to create the interactive GIS map. In addition, *Drill Data Maps* also created Excel spreadsheet templates for entering raw numeric field data and rock core lab data. MDT was responsible for incorporating the raw field data into the template. The interactive GIS database interface website provides access to all available raw data files. Development of the GIS data portal was coordinated with MDT's data management office to ensure compatibility with MDT systems and processes. The GIS website (https://expressway.app/portal/) will be maintained and available to the research team for the duration of the research project and the data collected will be available for future reference in a similar GIS database.

In addition to the creation of the GIS portal, a software package called *SiteTools* was developed by *Drill Data Maps* to allow users to analyze data files in assorted formats, merge data files of different types, build relationships between data types, export data to common formats (i.e., csv, xlsx), and develop correlations between the various MWD data components. As work progressed with the research team, it became clear that the (in progress) *SiteTools* package was not functioning as planned. Updates and patches were not effective. To maintain the project schedule as well as possible, the research team developed their own analysis tools using a *Matlab*®/spreadsheet based approach. These team developed tools were used for the remainder of the project.

To develop correlations, the collected (raw) data require preprocessing. This preprocessing step becomes complicated due to the large amount of collected data, the noisy nature of the collected MWD data and the various formats used to collect data from different sources, i.e., MWD data and subsurface property data rarely have compatible formats (Taleb et al. 2015; García et al. 2016; Klyuchnikov et al. 2019). In addition to MWD data, Montana Tech’s research team also included additional subsurface data such as natural moisture, soil/rock type, geologic formation identification, and unit weight to assist in developing correlations with the soil and rock strength data. These data were preprocessed for quality control and incorporated into spreadsheet files used by the research team.

The following figures (Figures 2 to 6) are sample screen shots from the data portal from user login to accessing the various data therein contained.

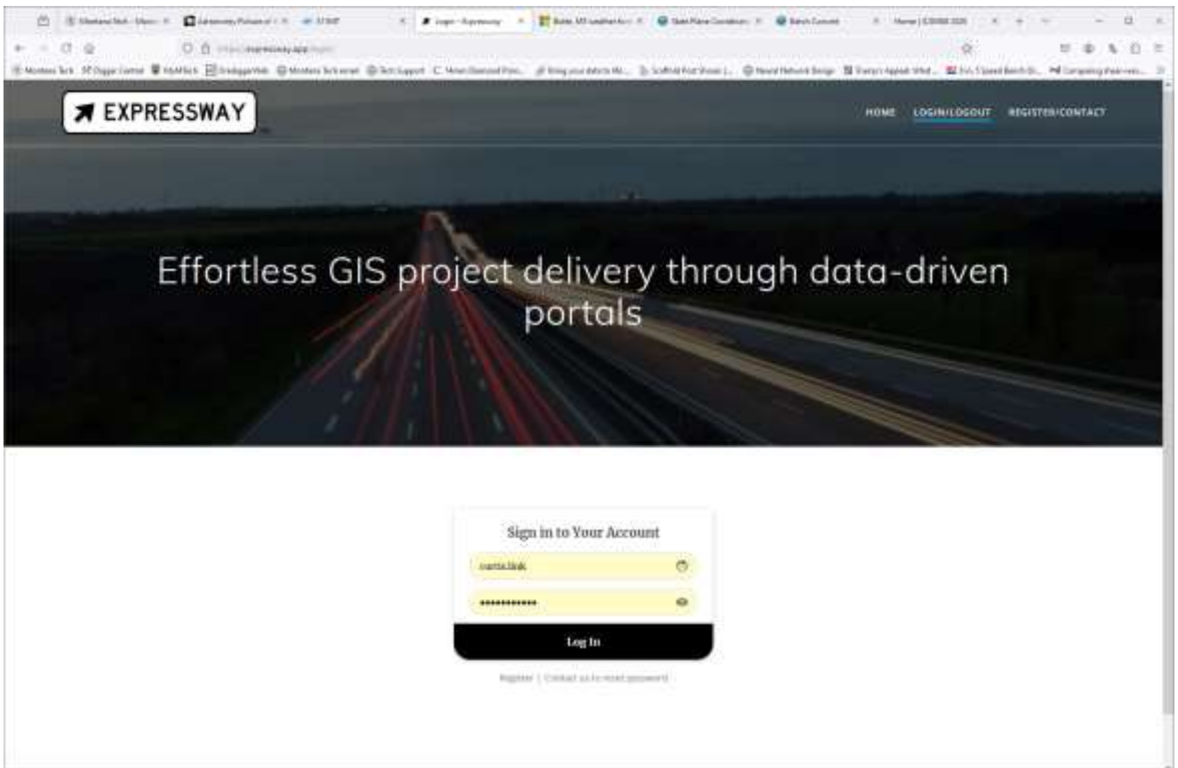

Figure 2. Login screen from Expressway Data Portal.

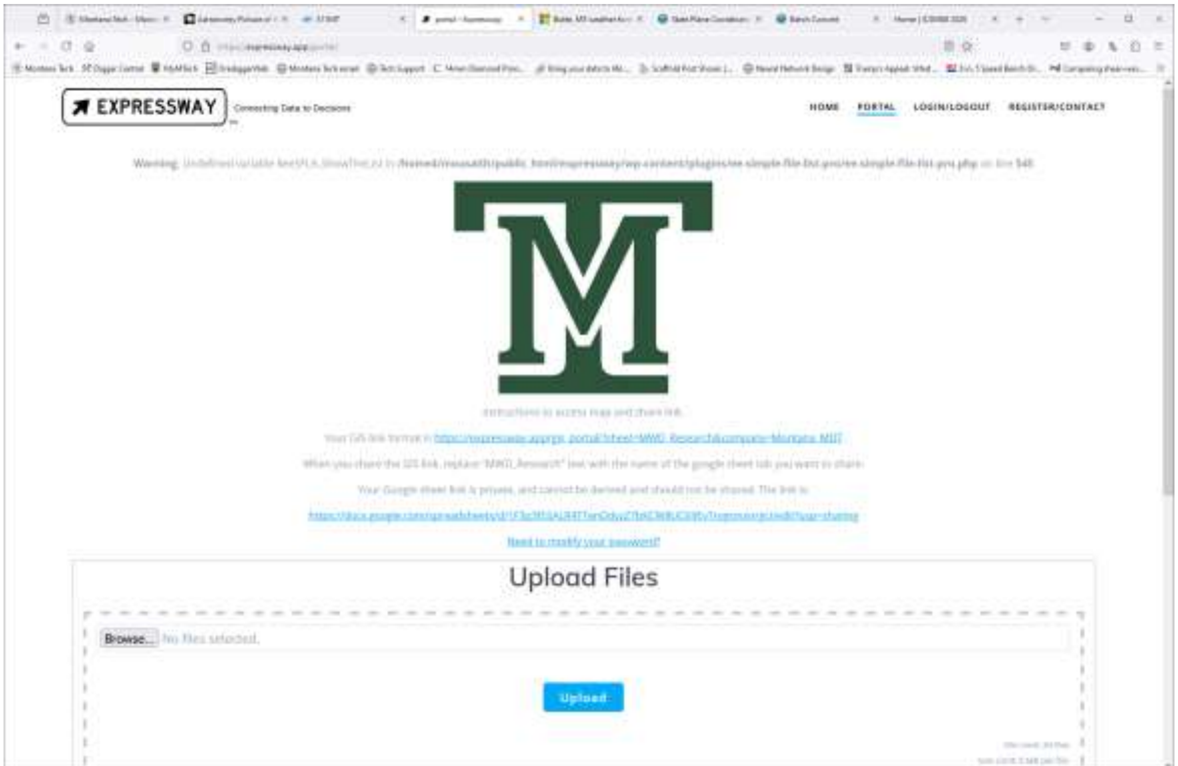

Figure 3. Access screen displaying active link (top link) for entering project site.

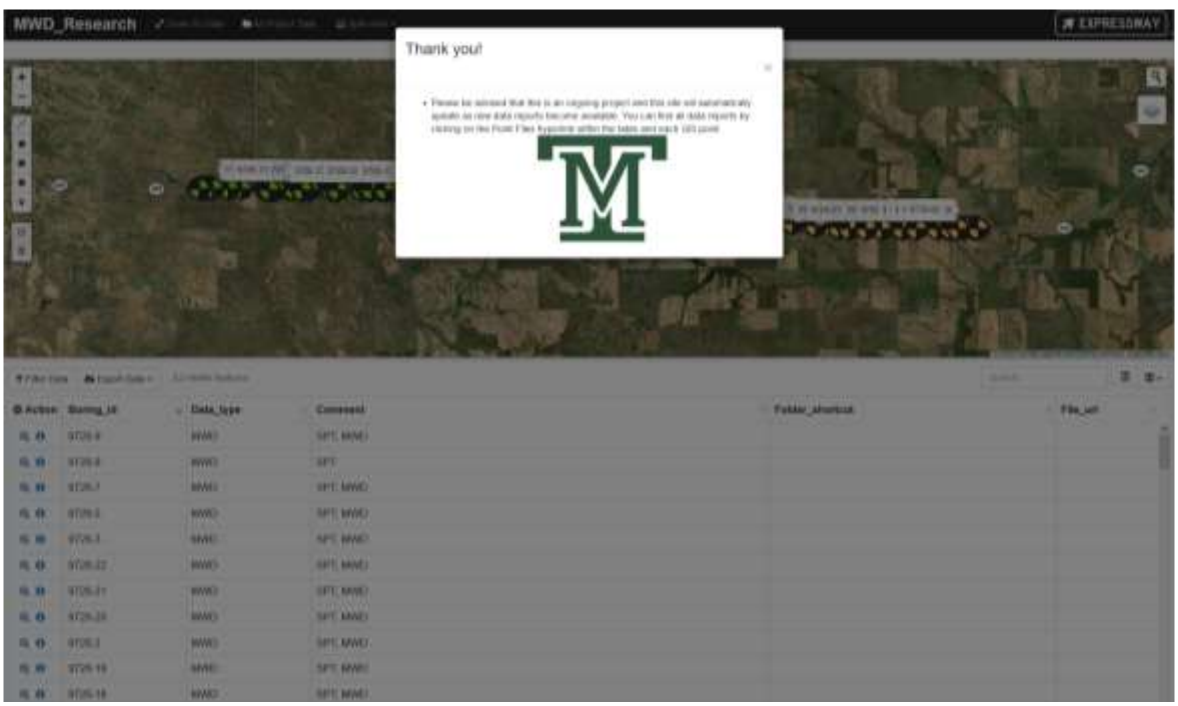

Figure 4. Splash screen indicating research project is ongoing and will be continually updated.

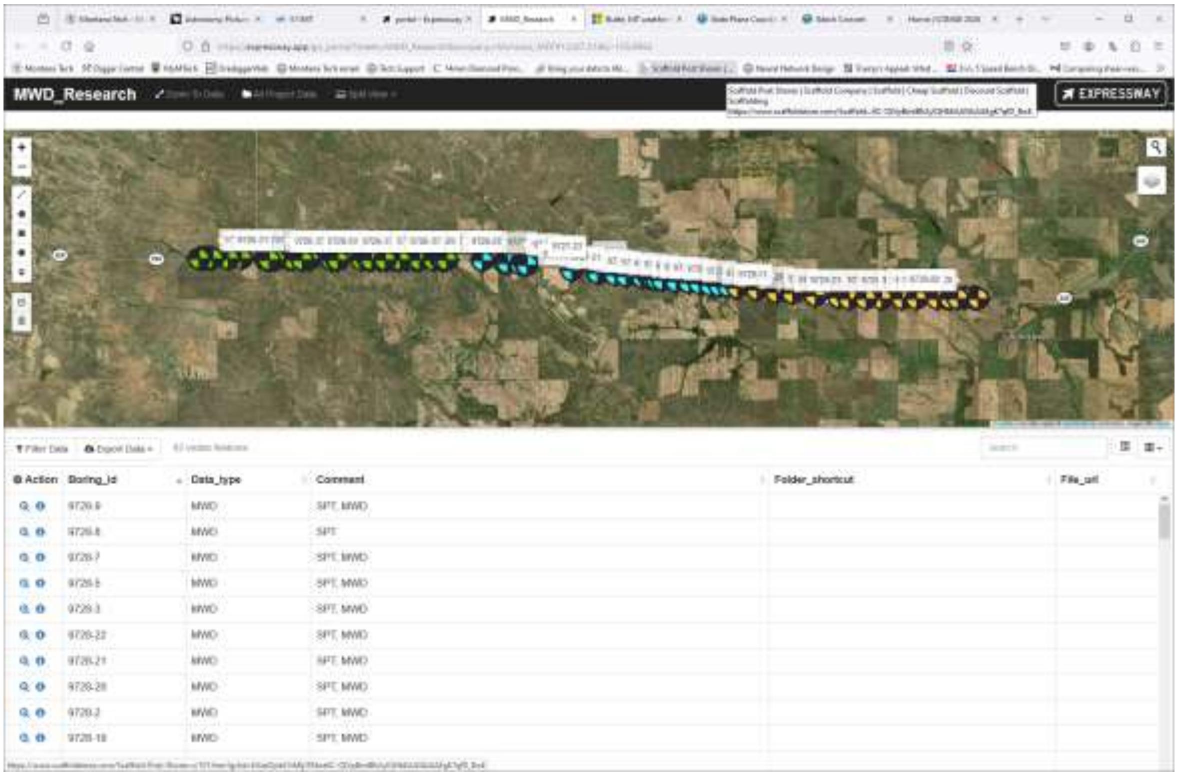

Figure 5. View of interactive map showing borehole numbering and list of data available for each borehole (scrollable).

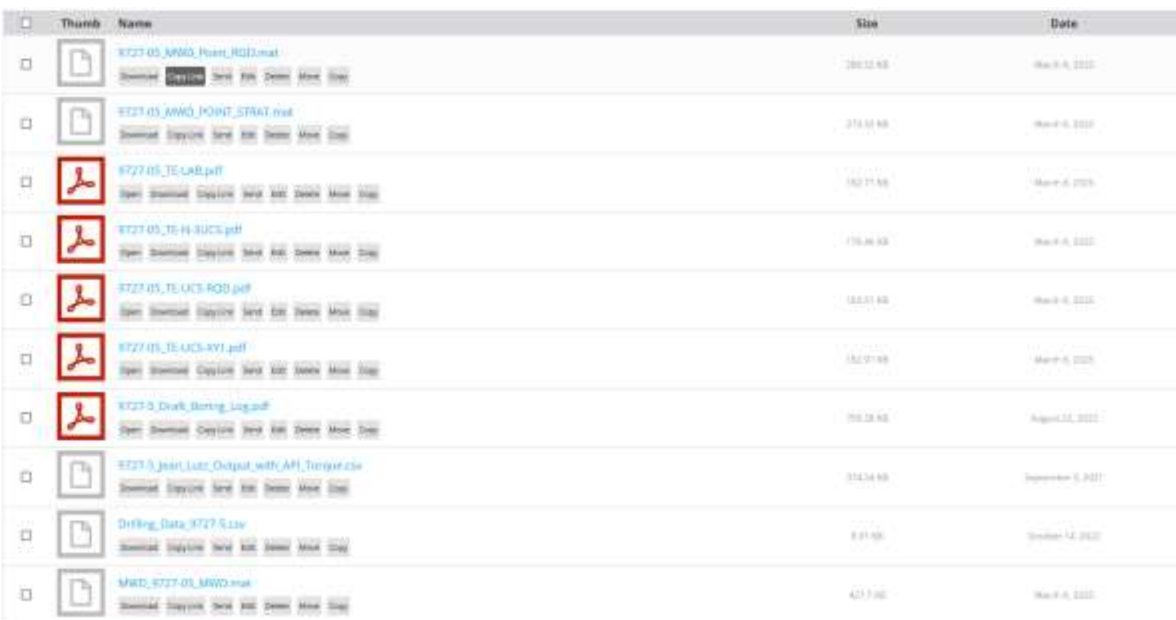

Figure 6. Example screen shot showing data types available for borehole 9727-05 with file size and upload date.

Table 1 show all MWD and laboratory data available on the portal to date. Data are listed in

Boring ID order. Boring ID numbers contain the MDT project control number (9728-, 9727-, 9726-) followed by the boring number for that control number (-28, -27, -26). The Comment column indicates the data types available. Finally, there is a column for MDT folder shortcuts and a File URL column indicating if Point Files (e.g., data entered into the spreadsheet templates, borehole logs, VST, PMT, etc.) are available for download.

Table 1. Comprehensive list showing all borehole information available on the portal. Data are identified by borehole ID which can be located on the interactive map by zooming in. Data used for analysis are indicated by 'Point Files' in last column which contain the raw data files.

Boring_id	Data_type	Comment	Folder_shortcut	File_url
9728-9	MWD	SPT, MWD		
9728-8	MWD	SPT		
9728-7	MWD	SPT, MWD		
9728-5	MWD	SPT, MWD		
9728-3	MWD	SPT, MWD		
9728-22	MWD	SPT, MWD		
9728-21	MWD	SPT, MWD		
9728-20	MWD	SPT, MWD		
9728-2	MWD	SPT, MWD		
9728-19	MWD	SPT, MWD		
9728-18	MWD	SPT, MWD		
9728-17	MWD	SPT, MWD		
9728-16	MWD	SPT, MWD		
9728-15	MWD	SPT, MWD		
9728-14	MWD	SPT, MWD		
9728-13	MWD	SPT, MWD		
9728-12	MWD	SPT, MWD		
9728-11	MWD	SPT, MWD		
9728-10	MWD	SPT, MWD		
9728-1	MWD	SPT, MWD		
9727-9	MWD	SPT, MWD		
9727-8	MWD	SPT, MWD		
9727-7	MWD	SPT, MWD, UCS	MWD_Research/9727000/9727-7	Point

				Files
9727-6	MWD	SPT, MWD		
9727-5	MWD	SPT, MWD, VST, UCS	MWD_Research/9727000/9727-5	Point Files
9727-4	MWD	SPT, MWD, VST	MWD_Research/9727000/9727-4	Point Files
9727-3	MWD	SPT, MWD		
9727-23	MWD	CSPT (1.875" DIA SPOON), MWD, VST, PMT, BST, UCS	MWD_Research/9727000/9727-23	Point Files
9727-22	MWD	CSPT (1.875" DIA SPOON), MWD, VST, PMT, BST, UCS	MWD_Research/9727000/9727-22	Point Files
9727-21	MWD	SPT, MWD		
9727-20	MWD	SPT, MWD		
9727-2	MWD	SPT, MWD		
9727-19	MWD	SPT, MWD		
9727-18	MWD	SPT, MWD		
9727-17	MWD	SPT, MWD		
9727-16	MWD	SPT, MWD		
9727-15	MWD	SPT, MWD		
9727-14	MWD	SPT, MWD		
9727-13	MWD	SPT, MWD, VST	MWD_Research/9727000/9727-13	Point Files
9727-12	MWD	SPT, MWD		
9727-11	MWD	SPT, MWD		
9727-10	MWD	SPT, MWD		
9727-1	MWD	SPT, MWD		
9726-9	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-9	Point Files
9726-8	MWD	SPT, MWD, VST, UCS	MWD_Research/9726000/9726-8	Point Files
9726-7	MWD	SPT	MWD_Research/9726000/9726-7	Point Files
9726-6	MWD	SPT		
9726-5	MWD	SPT, MWD		
9726-4	MWD	SPT, MWD		

9726-39	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-39	Point Files
9726-38	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-38	Point Files
9726-37	MWD	SPT, MWD		
9726-36	MWD	SPT, MWD		
9726-35	MWD	SPT, MWD		
9726-34	MWD	SPT, MWD		
9726-33	MWD	SPT, MWD		
9726-32	MWD	SPT, MWD		
9726-31	MWD	SPT, MWD, VST		
9726-30	MWD	SPT		
9726-3	MWD	SPT, MWD	MWD_Research/9726000/9726-3	Point Files
9726-29	MWD	SPT		
9726-28	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-28	Point Files
9726-27	MWD	SPT, MWD		
9726-26	MWD	SPT		
9726-25	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-25	Point Files
9726-24	MWD	SPT, MWD		
9726-23	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-23	Point Files
9726-22	MWD	SPT, MWD		
9726-21	MWD	SPT, MWD		
9726-20	MWD	SPT, MWD		
9726-2	MWD	SPT, MWD		
9726-19	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-19	Point Files
9726-18	MWD	SPT, MWD		
9726-17	MWD	SPT, MWD		
9726-16	MWD	SPT, MWD		
9726-15	MWD	SPT, MWD		

9726-14	MWD	SPT, MWD		
9726-13	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-13	Point Files
9726-12	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-12	Point Files
9726-11	MWD	SPT, MWD		
9726-10	MWD	SPT, MWD		
9726-1	MWD	SPT, MWD	MWD_Research/9726000/9726-1	Point Files

The preprocessing and analysis parts of the research use two main files: the Jean-Lutz MWD data file and a drilling data file. For example, for borehole 9727-5, the Jean-Lutz data are contained in a file named *9727-5_Jean_Lutz_Output_with_API_Torque.csv* which is then converted to an *xlsx* file for easier manipulation. Table 2 shows a portion of this file, which contains over 4,300 rows. Drilling stopped at 72 feet depth for this borehole. The file contains basic information about the borehole such as location and recorded parameters. Each sample (row) of the data file contains a time stamp, drilling depth, moving speed, down pressure, rotation speed, rotation torque (measured at the drive shaft), tool acceleration, flow rate, injection pressure, torque 2 (measured at the drill spindle), and two columns calculating the difference between the two measured torque values.

The drilling data for borehole 9727-5 are contained in the file *Drilling_Data_9727-5.csv*, which has also been converted to an *xlsx* file. Table 3 shows a large portion of this file. The file contains about 75 rows of data comprising drilling depth, sample thickness, offset, layer and sample IDs, stratigraphy and lithology IDs, top and bottom depths of samples, top and bottom elevations of samples, SPT blow count values, sample dry density, UCS, recovery, and RQD. In-situ shear strength (Su and Su_r) from vane shear testing were also included in the data for 9727-5, though these columns are not shown in the table to save room.

Both files were assembled using the templates created by *Drill Data Maps* and populated with the relevant information by MDT.

Table 2. Portion of Jean-Lutz data file 9727-5_Jean_Lutz_Output_with_API_Torque.xlsx used for analysis. Full data file contains over 4,300 rows.

		Measure Time	Depth (ft)	Moving Speed (ft/h)	Down Pressure (psi)	Rotation Speed (rev/min)	Rotation Torque (lbfft)	Rotation Torque (lbfft)_Converted_with_Gear_Factor_4.75	Tool Acceleration (g)	Flow (gal/min)	Injection Pressure (psi)	Torque 2 (psi)	Diff (%)	Difference (lb-ft)
Jobsite	WEST OF BROCKWAY WEST	0:00:00	0	0	46.45	0	136.58	648.7379275	-0.01	0	-1.24	-123	294%	771.7379
Contract	9727	0:00:00	0	0	45.98	0	136.85	650.0203938	0	0	-1.27	-122.6	293%	772.6204
Machine	1050	0:00:00	0	0	45.98	0	136.85	650.0203938	0	0	-1.27	-122.6	293%	772.6204
Survey Name	5	0:00:00	0	0	45.98	0	136.85	650.0203938	0	0	-1.27	-122.6	293%	772.6204
Start date	8/17/2021 8:28	0:00:00	0	0	45.98	0	136.85	650.0203938	0	0	-1.27	-122.6	293%	772.6204
Stop Date	8/17/2021 14:14	0:00:00	0	0.02	32.07	0	117.4	557.635325	-0.01	0	-1.17	-62.6	251%	620.2353
Length (m)	21.34	0:00:00	0	0.02	35.99	0	3.19	15.15210125	-0.02	0	-1.2	-1.1	231%	16.2521
		0:00:00	0	0.02	35.87	0	-2.67	-12.68216625	-0.02	0	-1.15	-1.1	168%	-11.5822
		0:00:00	0	0.02	35.66	0	-2.67	-12.68216625	-0.01	0	-1.18	-1.2	165%	-11.4822
		0:00:00	0	0.02	35.83	0	3.3	15.6745875	-0.01	0	-1.19	-1.1	230%	16.77459
		0:00:00	0	0.02	36.64	0	3.27	15.53209125	0	0	-1.19	-1.1	230%	16.63209
		0:00:00	0	0.02	36.51	0	3.26	15.4845925	0	0	-1.15	1.1	173%	14.38459
		0:00:00	0	0.02	36.22	0	3.06	14.5346175	0	0	-1.12	-1.3	239%	15.83462
		0:00:00	0	0.02	36.96	0	3.17	15.05710375	0.01	0	-1.16	1.2	170%	13.8571
		0:00:00	0	0.02	36.91	0	3.18	15.1046025	0.01	0	-1.11	1.1	173%	14.0046
		0:00:00	0	0.02	36.63	0	3.18	15.1046025	0.01	0	-1.12	1.1	173%	14.0046
		0:00:00	0	0.02	37.47	0	3.25	15.43709375	0.01	0	-1.18	1	176%	14.43709
		0:00:01	0	0.02	37.94	0	3.19	15.15210125	0.02	0	-1.24	0.9	178%	14.2521
		0:00:02	0	12.2	45.56	0	3.27	15.53209125	0.01	0	-1.27	0.9	178%	14.63209
		0:00:03	0.03	81.24	81.01	0	3.37	16.00707875	0	0	-1.22	0.8	181%	15.20708
		0:00:04	0.06	99.25	99.47	0	3.3	15.6745875	-0.01	0	-1.16	0.9	178%	14.77459
		0:00:05	0.1	158.21	166.51	0	3.4	16.149575	-0.01	0	-1.19	0.8	181%	15.34958
		0:00:06	0.14	156.06	165.07	0	3.58	17.0045525	-0.01	0	-1.21	0.7	184%	16.30455
		0:00:07	0.18	157	167.24	0	2.89	13.72713875	0	0	-1.14	1	173%	12.72714
		0:00:07	0.22	157.14	167.12	0	3.23	15.34209625	0	0	-1.16	0.8	180%	14.5421
		0:00:08	0.27	155.86	169.38	0	3.1	14.7246125	0	0	-1.21	0.9	177%	13.82461
		0:00:09	0.31	151.6	184.71	0	3.19	15.15210125	0	0	-1.28	1	175%	14.1521
		0:00:10	0.35	149.5	219.72	0	3.27	15.53209125	0.01	0	-1.32	0.9	178%	14.63209
		0:00:12	0.39	143.69	258.04	0	3.67	17.43204125	0.01	0	-1.22	1	178%	16.43204
		0:00:13	0.43	146.96	325.86	0	3.32	15.769585	0	0	-1.24	1	176%	14.76959
		0:00:14	0.48	147.51	397.77	0	3.05	14.48711875	0	0	-1.28	1	174%	13.48712
		0:00:15	0.52	146.16	462.25	0	3.47	16.48206625	0	0	-1.19	1	177%	15.48207
		0:00:15	0.56	174.17	410	0	103.27	490.5195913	0.28	0	-1.15	0.9	199%	489.6196
		0:00:16	0.6	167.49	302.43	0	119	565.235125	0.83	0	-1.19	0.8	199%	564.4351
		0:00:17	0.65	151.96	282.65	2.58	103.81	493.0845238	0.62	0	-1.16	0.8	199%	492.2845
		0:00:18	0.69	160.73	291.05	20.66	115.01	546.2831238	0.4	0	-1.18	1	199%	545.2831
		0:00:19	0.73	151.38	303.66	20.96	138.68	658.712665	0.27	0	-1.16	0.8	200%	657.9127
		0:00:20	0.78	153.21	307.87	21.46	144.86	688.0668925	0.17	0	-1.16	0.9	199%	687.1669
		0:00:21	0.82	160.9	312.96	21.26	151.32	718.751085	0.11	0	-1.22	0.9	199%	717.8511
		0:00:22	0.86	147.97	342.61	21.3	160.43	762.0224463	0.07	0	-1.2	1	199%	761.0224
		0:00:23	0.9	160.65	353.61	23.29	157.58	748.4853025	0.04	0	-1.19	1	199%	747.4853
		0:00:24	0.95	159.08	374.88	30.85	155.62	739.1755475	0.02	0	-1.23	1	199%	738.1755
		0:00:25	0.99	168.96	369.4	33.73	154.15	732.1932313	0.01	0	-1.24	0.8	200%	731.3932
		0:00:26	1.03	160	378.41	34.39	156.7	744.3054125	0	0	-1.17	0.9	200%	743.4054
		0:00:27	1.08	165.59	374.65	34.59	154.92	735.850635	0	0	-1.17	0.9	200%	734.9506
		0:00:28	1.12	160.53	381.52	34.69	157.59	748.5328013	-0.01	0	-1.14	1	199%	747.5328
		0:00:29	1.16	160.13	374.93	34.71	159.8	759.030025	-0.01	0	-1.14	0.9	200%	758.13
		0:00:30	1.2	159.01	377.01	34.71	164.39	780.8319513	-0.01	0	-1.18	0.9	200%	779.932
		0:00:31	1.25	155.9	384.51	34.73	167.12	793.79911	0	0	-1.22	0.9	200%	792.8991
		0:00:32	1.29	164.2	382.66	34.65	168.93	802.3963838	0.01	0	-1.19	0.9	200%	801.4964
		0:00:33	1.33	156.72	393.55	34.66	172.18	817.8334775	0.02	0	-1.16	0.7	200%	817.1335
		0:00:34	1.37	166.45	397.85	34.65	169.19	803.6313513	0.02	0	-1.14	0.8	200%	802.8314
		0:00:35	1.42	158.89	407.27	34.66	177.63	843.7202963	0.02	0	-1.08	0.9	200%	842.8203
		0:00:36	1.46	166.66	400.84	34.61	176.14	836.6429825	0.01	0	-1.13	0.7	200%	835.943
		0:00:37	1.5	159.35	415.5	34.56	180.24	856.11747	0	0	-1.06	0.9	200%	855.2175
		0:00:38	1.54	162.82	413.76	34.56	181.51	862.1498113	0	0	-1.16	0.8	200%	861.3498
		0:00:39	1.59	162.74	424.43	34.55	187.57	890.9340538	0	0	-1.19	0.7	200%	890.2341
		0:00:39	1.63	157.47	423.52	34.49	191.38	909.0310775	0	0	-1.17	0.7	200%	908.3311
		0:00:40	1.68	165.59	431.23	34.45	193.95	921.2382563	0	0	-1.18	0.8	200%	920.4383
		0:00:41	1.72	156.46	431.1	34.43	199.59	948.0275513	0	0	-1.13	0.8	200%	947.2276
		0:00:42	1.76	167.4	435.17	34.33	197.8	939.525275	-0.01	0	-1.1	0.7	200%	938.8253
		0:00:43	1.8	155.85	441.2	34.37	205.74	977.2392825	-0.01	0	-1.19	0.8	200%	976.4393
		0:00:44	1.84	164.54	442.8	34.31	207.14	983.8891075	-0.01	0	-1.11	0.8	200%	983.0891
		0:00:45	1.89	160.31	448.55	34.22	218.4	1037.3727	-0.01	0	-1.12	1	200%	1036.373
		0:00:46	1.93	166.2	434.64	34.14	211.28	1003.55359	-0.01	0	-1.11	0.8	200%	1002.754
		0:00:47	1.97	129.46	407.5	34	214.23	1017.565721	0	0	-1.17	0.8	200%	1016.766
		0:00:48	2	131.9	395.03	34.11	202.93	963.8921338	0.01	0	-1.17	0.8	200%	963.0921

Table 3. Portion of drilling data file Drilling_Data_9727-5.xlsx used for analysis. Full data file contains about 75 rows.

Jobsite	West of Brockway-West																	
Contra	9727000																	
HoleID	9727-5																	
Northir	1139540.507																	
Easting	2828864.6																	
Elevati	2535.83																	
Latitud	47.32348968																	
Longitu	-106.0278662																	
Start D	8/17/2021 8:28																	
Date	8/17/2021																	
RigID	1050																	
Depth (ft)	Thickness (ft)	Offset (ft)	LayerID	SampleID	Stratigraphy ID	Lithology ID	Top_Depth (ft)	Bottom_Depth (ft)	Top_El	Bottom_El	N1	N2	N3	N	DD (pcf)	UCS (psi	REC	RQD
2.75	0.5	0	9727-05-SPT-1	9727-05-SPT-1-N1			2.5	3	2533.33	2532.83	2							
3.25	0.5	0	9727-05-SPT-1	9727-05-SPT-1-N2			3	3.5	2532.83	2532.33		3						
3.5	1	0	9727-05-SPT-1	9727-05-SPT-1-N			3	4	2532.83	2531.83				6				
3.75	0.5	0	9727-05-SPT-1	9727-05-SPT-1-N3			3.5	4	2532.33	2531.83			3					
5.25	0.5	0	9727-05-SPT-2	9727-05-SPT-2-N1			5	5.5	2530.83	2530.33	2							
5.75	0.5	0	9727-05-SPT-2	9727-05-SPT-2-N2			5.5	6	2530.33	2529.83		2						
6	1	0	9727-05-SPT-2	9727-05-SPT-2-N			5.5	6.5	2530.33	2529.33				5				
6.25	0.5	0	9727-05-SPT-2	9727-05-SPT-2-N3			6	6.5	2529.83	2529.33			3					
7.75	0.5	0	9727-05-SPT-3	9727-05-SPT-3-N1			7.5	8	2528.33	2527.83	0							
8.25	0.5	0	9727-05-SPT-3	9727-05-SPT-3-N2			8	8.5	2527.83	2527.33		2						
8.5	1	0	9727-05-SPT-3	9727-05-SPT-3-N			8	9	2527.83	2526.83				4				
8.75	0.5	0	9727-05-SPT-3	9727-05-SPT-3-N3			8.5	9	2527.33	2526.83			2					
10.25	0.5	0	9727-05-SPT-4	9727-05-SPT-4-N1			10	10.5	2525.83	2525.33	2							
10.4	0.7	0	9727-05-VST-1															
10.75	0.5	0	9727-05-SPT-4	9727-05-SPT-4-N2			10.5	11	2525.33	2524.83		3						
11	1	0	9727-05-SPT-4	9727-05-SPT-4-N			10.5	11.5	2525.33	2524.33				5				
11.25	0.5	0	9727-05-SPT-4	9727-05-SPT-4-N3			11	11.5	2524.83	2524.33			2					
12.75	0.5	0	9727-05-SPT-5	9727-05-SPT-5-N1			12.5	13	2523.33	2522.83	3							
13.25	0.5	0	9727-05-SPT-5	9727-05-SPT-5-N2			13	13.5	2522.83	2522.33		5						
13.5	1	0	9727-05-SPT-5	9727-05-SPT-5-N			13	14	2522.83	2521.83				13				
13.75	0.5	0	9727-05-SPT-5	9727-05-SPT-5-N3			13.5	14	2522.33	2521.83			8					
15.25	0.5	0	9727-05-SPT-6	9727-05-SPT-6-N1			15	15.5	2520.83	2520.33	1							
15.75	0.5	0	9727-05-SPT-6	9727-05-SPT-6-N2			15.5	16	2520.33	2519.83		5						
16	1	0	9727-05-SPT-6	9727-05-SPT-6-N			15.5	16.5	2520.33	2519.33				11				
16.25	0.5	0	9727-05-SPT-6	9727-05-SPT-6-N3			16	16.5	2519.83	2519.33			6					
20.25	0.5	0	9727-05-SPT-7	9727-05-SPT-7-N1			20	20.5	2515.83	2515.33	11							
20.75	0.5	0	9727-05-SPT-7	9727-05-SPT-7-N2			20.5	21	2515.33	2514.83		14						
21	1	0	9727-05-SPT-7	9727-05-SPT-7-N			20.5	21.5	2515.33	2514.33				40				
21.25	0.5	0	9727-05-SPT-7	9727-05-SPT-7-N3			21	21.5	2514.83	2514.33			26					
25.25	0.5	0	9727-05-SPT-8	9727-05-SPT-8-N1			25	25.5	2510.83	2510.33	14							
25.75	0.5	0	9727-05-SPT-8	9727-05-SPT-8-N2			25.5	26	2510.33	2509.83		25						
26	1	0	9727-05-SPT-8	9727-05-SPT-8-N			25.5	26.5	2510.33	2509.33				64				
26.25	0.5	0	9727-05-SPT-8	9727-05-SPT-8-N3			26	26.5	2509.83	2509.33			39					
27.5	0.6	0	9727-05-C-1	9727-05-UCS-01			27.2	27.8	2508.63	2508.03					102	21		
27.5	5	0	9727-05-C-1				25	30	2510.83	2505.83							66	12
31.05	0.7	0	9727-05-C-2	9727-05-UCS-02			30.7	31.4	2505.13	2504.43					111.8	59		
31.5	0.6	0	9727-05-C-3	9727-05-UCS-03			31.2	31.8	2504.63	2504.03					108.4	136		
32.3	0.6	0	9727-05-C-4	9727-05-UCS-04			32	32.6	2503.83	2503.23					109.4	48		
32.5	5	0	9727-05-C-2				30	35	2505.83	2500.83							100	86
32.9	0.6	0	9727-05-C-5	9727-05-UCS-05			32.6	33.2	2503.23	2502.63					109	133		
34.8	0.6	0	9727-05-C-6	9727-05-UCS-06			34.5	35.1	2501.33	2500.73					105.9	61		
35.6	0.6	0	9727-05-C-7	9727-05-UCS-07			35.3	35.9	2500.53	2499.93					98.79	12		
37.5	5	0	9727-05-C-3				35	40	2500.83	2495.83							80	30
40.65	0.3	0	9727-05-C-8	9727-05-UCS-08			40.5	40.8	2495.33	2495.03					90.5	30		
41.25	0.3	0	9727-05-C-9	9727-05-UCS-09			41.1	41.4	2494.73	2494.43					72.4	225		
41.55	0.3	0	9727-05-C-10	9727-05-UCS-10			41.4	41.7	2494.43	2494.13					71.9	320		
41.7	0.2	0	9727-05-C-11	9727-05-UCS-11			41.6	41.8	2494.23	2494.03					83.4	80		
42.1	0.6	0	9727-05-C-12	9727-05-UCS-12			41.8	42.4	2494.03	2493.43					89.9	288		
42.5	5	0	9727-05-C-4				40	45	2495.83	2490.83							100	34
42.95	0.3	0	9727-05-C-13	9727-05-UCS-13			42.8	43.1	2493.03	2492.73					87.3	87		
46.7	0.6	0	9727-05-C-14	9727-05-UCS-14			46.4	47	2489.43	2488.83					105.2	14		
47.5	5	0	9727-05-C-5				45	50	2490.83	2485.83							100	52
47.7	0.6	0	9727-05-C-15	9727-05-UCS-15			47.4	48	2488.43	2487.83					112.3	71		
48.5	0.6	0	9727-05-C-16	9727-05-UCS-16			48.2	48.8	2487.63	2487.03					108.5	96		
51.1	0.6	0	9727-05-C-17	9727-05-UCS-17			50.8	51.4	2485.03	2484.43					109.8	51		
51.8	0.6	0	9727-05-C-18	9727-05-UCS-18			51.5	52.1	2484.33	2483.73					114.4	255		
52.4	0.6	0	9727-05-C-19	9727-05-UCS-19			52.1	52.7	2483.73	2483.13					113.2	111		
52.5	5	0	9727-05-C-6				50	55	2485.83	2480.83							96	68

4. Preprocessing and Quality Control

MWD data types used for this project consisted of hollow stem auger (HSA) data and HQ rock coring data below HSA refusal, extending to the borehole bottom. Quality control and data parsing were performed for both types of data.

4.1. HSA Data

Figure 7 is an example of MWD data from borehole 9727-7 showing HSA drilling from 0 to 35 feet and rock coring data from 35 feet to approximately 72 feet depth. This figure shows continuous MWD data recording with depth; however, red arrows indicate where sharp drops and subsequent gaps in down pressure (green trace) and torque (red trace) measurements are observed. This phenomenon is also observed in the moving speed and rotation speed traces, though it is not as profound as with down pressure and torque. These gaps appear to occur at approximate 5-foot depth intervals, where drilling was stopped to perform a SPT and split spoon sampling and to add another 5-foot auger section. Initial observation suggested that the observed sudden drops and gaps in data might be a result of drilling through the hole in the subsurface as a result of the split spoon sampling. Another explanation might be that this might be more influenced by the drill string re-engaging prior to making contact with the subsurface after the addition of each new auger section. Because of this effect, any analysis using particularly down pressure or torque cannot simply use the recorded data as is from the data file at those depths. Our first preprocessing/quality control step was to manually extract the last recorded down pressure and torque measurement prior to the sudden drop occurring when adding additional HSA auger sections.

For HSA analysis, rather than using the continuous down pressure and torque data traces, we determined that we could only use the individual down pressure and torque values just prior to the sudden drop, as indicated by arrows on the plot. This greatly reduces the amount of data that can be used for analysis. In addition, the amount of effort necessary to extract data for analysis is greatly increased because this is done by visual inspection. As the MWD data are in spreadsheet format (i.e., all measured quantities at a specific time/depth), only the data from depths identified with the red arrows would be kept for analysis.

Future work should focus on how MWD data are collected to mitigate this problem and/or developing an automated approach to extract the relevant down pressure data points (and associated measurements in the same row) to streamline the analysis data flow. One possible solution suggested by experienced geotechnical engineers is to drill a second borehole adjacent the first borehole to eliminate gaps in data due to the SPT and split spoon sampling. Split spoon sampling and rock coring would be accomplished in borehole 1. In borehole 2, MWD data collection would take place continuously within the limits of lengths of drill sections. Drillers would also be trained for optimum starting/stopping MWD recording to reduce gaps in data due to the addition of new auger sections.

4.2. Rock Coring Data

Rock coring data were also entered into the Drilling Data template by MDT. The template has columns for entry of depth and thickness of sample, IDs for the sample, elevations of the top and bottom of the sample, SPT blow counts and lab measurements such as dry density, UCS, Rec, RQD and Su. Table 3 shows a portion of the rock coring data for borehole 9727-5. The rock coring data were reviewed by an experienced research team member for quality control prior to analysis.

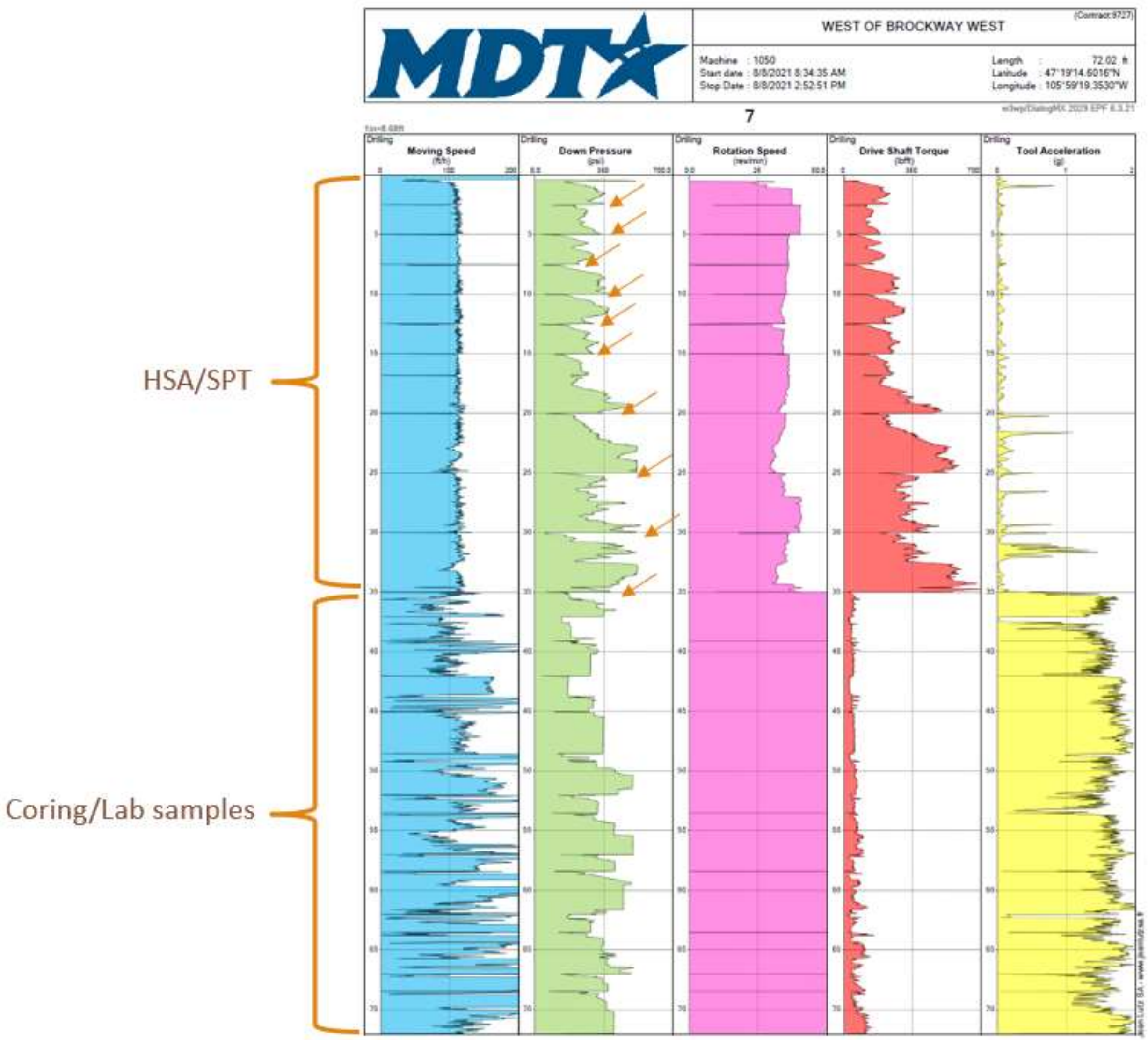

Figure 7. MWD data from borehole 9727-7 showing HSA depth section and rock coring section. Note arrows on Down Pressure plot (green) showing sharp drop in down pressure when drilling stopped.

5. Data Formatting for Analysis

Data analysis took two forms: 1) correlation of MWD data with SPT blow counts for the HSA drilled section, and 2) correlation of MWD data with UCS and unit weight for the cored section. In addition to the raw MWD data, we calculated what are referred to as compound parameters. Compound parameters are a combination or function of individual drilling parameters that allow comparison of soil and site conditions while limiting the influence of changing drilling conditions and drilling operator choices (Baser et al. 2023/4).

5.1. Compound Parameters

We calculated and investigated three compound parameters as functions of four drilling parameters. The four MWD drilling parameters used for calculating compound parameters were:

- Peak down pressure (psi)
- Rotation torque (lb-ft)
- Rotation speed (rev/min)
- Moving speed (ft/h)

The compound parameters we investigated are:

- Specific drilling energy (Teale 1956),
- Somerton index (Somerton 1959) and
- Drilling energy (Pfister 1985).

Equations 1 to 3 show the formulas used to calculate each of the investigated compound parameters:

$$\text{Specific drilling energy} = \frac{F}{A} + \frac{2\pi NT}{AV} \tag{1}$$

$$\text{Somerton index} = \frac{P}{\sqrt{V}} \tag{2}$$

$$\text{Drilling energy} = \frac{TN}{V} \tag{3}$$

where

$$\frac{F}{A} = P = down\ pressure$$
$$N = rotation\ rate$$
$$T = torque$$
$$A = area$$
$$V = penetration\ rate.$$

Drilling parameters are typically recorded in a variety of convenient drilling units. For compound parameter calculations, we converted each drilling parameter to SI units and then converted the final compound parameter SI value to units more amenable to interpretation. Ultimately our compound parameter of choice was *specific drilling energy* which was used as an additional input in our correlation analyses.

5.2. Final Data Assembly

The last step of data preprocessing was assembling the spreadsheets to be used for Task 2 analysis. After data organization and quality control, the final data to be used for analysis were brought together into a single 'master' spreadsheet. Simple correlations could be calculated within the spreadsheet or data from the spreadsheet could be exported into the Matlab® based scripts developed by the research team. The data will be further analyzed and correlations discussed in the forthcoming Task 2 report.

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