Organization and Analysis of MWD Data

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

No figures

PROBLEM STATEMENT

Obtaining sufficient and reliable in-situ geologic substrate data and characterizing the subsurface conditions for engineering design purposes has always been a challenge to the natural resources and civil engineering industries. Availability and accuracy of such information are key, however, for the successful planning, design, construction, and operation of many engineering projects, including transportation infrastructure. Measurement While Drilling (MWD) technology has shown great potential for improving the subsurface characterization process in some industries. Since the 1980s, for example, MWD has been critical to the development of directional drilling within the petroleum industry. In the geotechnical engineering industry, however, MWD technology is in early research stages.

Utilizing a $50,000 contract funded in early 2020 through FHWA's Every Day Counts (EDC) 5 Initiative, the Montana Department of Transportation (MDT) is currently evaluating the MWD technology on their Central Mine Equipment (CME) 1050 ATM drill rig. For the past several months, MDT has been collecting continuous and consistent measurements of MWD data at several of their projects. The collected data include drilling depth, drilling rate, rotation speed, down pressure, hold-back pressure, mast vibration, flow rate, and fluid pressure. MDT will continue to collect more MWD data with an attempt to also collect accurate mechanical torque data. It is worth mentioning that other data including the standard penetration test (SPT), vane shear test (VST), cone penetration test (CPT), pressuremeter test (PMT), as well as geophysical survey data, can also be collected. These data will be collected at MDT project sites that have proposed cuts, embankment fills, culverts, and bridge foundations and will be assembled into a comprehensive database. The challenges with MWD technology include a combination of organizing large amounts of collected data and correlating these data to the desired subsurface characteristics such as the subsurface soil and rock strength parameters. Finding meaningful and reliable correlations using the comprehensive database will be the focus of MWD data analysis.

BACKGROUND SUMMARY

Design and construction of any foundation, especially deep foundations in transportation infrastructure projects, require sufficient and 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 throughout the project site. For instance, the stratigraphy and the strength characteristics of the subsurface underneath the different piers of a bridge at a project site could vary significantly. Rodgers et al. (2018) reported, for example, that the measured mean unconfined compressive strengths (UCS) of two individual borings located only 5 meters apart at adrilled shaft site in Fort Lauderdale, Florida, were about 50 percent different. Meanwhile, foundation design is evolving to adopt the load and resistance factor design (LRFD), which separately incorporates the uncertainties related to each load and resistance component (Rodgers et al. 2018a). Higher resistance factors could be used for the foundation design in a project site if the required strength parameters could be measured at each location of interest within the project site, which could significantly improve the design and reduce the costs. In the case of the mentioned drilled shaft site in Fort Lauderdale, Florida reported by Rodgers et al. (2018), for example, higher resistance factors can be used as the UCS of the rock is measured for each drilled shaft and the uncertainty related to the strength is reduced. Using the higher resistance factors, in this case, would decrease the total costs of the project. UCS that is needed in the foundation designs, however, is rarely measured within the footprint of each shaft which means a lower resistance factor would be typically used for the entire site. In general, limited in-situ data and the time-consuming/costly nature of sampling and laboratory testing of different layers are usually major constraints in obtaining sufficient information especially in areas with highly variable stratigraphy. Hence, having a means of estimating the strength of subsurface strata at every location of interest in a project would be of high value. This is where estimating (correlating) the strength data from parameters that could be readily measured during the drilling operation at a site would become valuable.

Fortunately, Measurement While Drilling (MWD) technology has shown potential to improve the assessment of the variability of soil/rock layers and their strength characteristics. Specifically, MWD has been successfully used for improving subsurface characterization in the natural resources 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, for example, MWD has been critical to the development of directional drilling within the petroleum industry, e.g., (Barr 1984; McKenney and Knoll 1989; Pittard et al. 1989). In the geotechnical engineering industry, however, MWD technology is in early research stages (Bishara and McReynolds 1990; Schunnesson 1996; Gui et al. 2002; Sadkowski et al. 2010; Reiffsteck 2011; Laudanski etal. 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 the geotechnical industry. With few exceptions, the correlations developed between MWD parameters and geomaterial strengths for the energy resources industry usually contain coefficientsfor 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 the drilling practices used in geotechnical engineering, e.g., auger bits thatare usually used in drilled shafts projects (Rodgers et al. 2018a). In fact, according to Bingham (1964), there are about 26 parameters that could influence drilling and in turn, affect the correlation between the MWD parameters and the rock strength.

According to Karasawa et al. (2002a, 2002b), the correlation developed between the MWD parameters and the rock strength could be different in soft, medium, and hard rocks, unless a universal correlation is examined. This is correct for geotechnical correlations as well and the correlations mentioned above are only derived based on soft 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 the MWD data and therefore the derived correlations. They also emphasize that the type of drilling tool (bit) plays a very important role in the developed 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. One of the main purposes of this study is to investigate the data collected through the MWD program of MDT, develop correlations between the measured data and the 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 intermediate geomaterials (IGM's) 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.

As part of this research project, a consultant will be hired to perform in-situ pressuremeter testing (PMT) within IGM’s to supplement the other, more traditionally collected data. Many successful correlations have been evaluated between PMT results and other insitu testing data, such as UCS. Very little information is available relating the results of PMT to MWD parameters, though it is a topic of increased interest in the quickly growing MWD testing community. Pressuremeter testing will be performed in a minimum of two borings. During the pressuremeter test, a probe will be inserted into a drilled boring and lowered to the depth of interest. The probe will then be inflated, and pressure will be applied to the sidewalls of the boring. As the pressure is increased, the walls of the boring will deform and volume change will be measured. The PMT will provide a direct measurement of the in-situ earth pressure and soil modulus, which can be directly correlated to other in-situ soil/rock strength parameters and measured MWD parameters.

BENEFITS AND BUSINESS CASE

Organizing, analyzing, and interpreting the MWD data is of great importance and urgency to MDT as it can benefit the organization in several ways.

First, an online database will allow MDT to display and exchange MWD and related data in an easy-to-use GIS platform.

Second, a lack of information about the substrata in a project may result in construction change orders requested by contractors. These change orders are not only costly but also time- consuming and usually end up altering the completion dates. The FHWA has hypothesizedthat collecting and interpreting MWD data could help to reduce the number of such requests significantly.

Third, the information obtained through the MWD process could increase the drilling efficiency by guiding the drillers on choosing the optimum drilling rate, flow rate, injection pressure, etc. This will help to ensure efficient drilling techniques and proper tooling are used.

Fourth, based on MDT's conversations with their drillers, the MWD process will not only provide education but also increase the excitement and engagement of drillers.

Finally, the interpreted data can be used in determining the index and engineering properties of the subsurface layers in a more consistent and continuous manner. MWD has the potential to provide a continuous detailed and accurate record of geotechnical subsurface characteristics (strength versus depth, CPT-like index graphs, presence of subsurface voids, fissures and other anomalies). This could improve the project's design recommendations and potentially even reduce the number of subsurface exploration locations required for a project. A reduction of subsurface exploration locations and an increase of subsurface data will likely result in significant cost savings.

OBJECTIVES

The outcome of this research project is the organization and interpretation of geotechnical drilling data and the evaluation of existing correlations between MWD data and subsurface strength and index properties and the creation of newly developed correlations. The correlation equations can then be readily used to optimize the number of required subsurface exploration locations, reduce sampling intervals, improve project understanding, and potentially reduce the number of change orders. Therefore, the only possible implementation barrier for this project would be the cost and staffing requirements for conducting MWD in future MDT projects. However, as MDT has already installed all the required sensors on one of their drill rigs and their staff (drillers) are trained and currently using the equipment in some of their projects, these barriers would be minimal.

RESEARCH PLAN

In this research, MWD data collected by MDT will be organized, processed, and analyzed. Correlations between MWD data and subsurface properties, specifically soils and rocks strengths, will be developed.

Task 1: Organization and preprocessing of collected data

To develop correlations, the collected (raw) data needs to be preprocessed. This preprocessing step is rather complicated due to the large number of collected data, the noisy nature of collected MWD data, and different formats usually used to collect data from different sources, i.e., MWD data and subsurface properties data rarely have completely compatible formats (Taleb et al. 2015; García et al. 2016; Klyuchnikov et al. 2019). The preprocessing of the data will also be conducted in the first step of this research.

In this step, the MDT's collected field data, as well as CPT, VST, PMT, SPT, geophysics, in- situ, and laboratory obtained soil and rock shear strength testing data will be organized and placed on a GIS-based interactive map on a website. Drill Data Maps will be hired as an outside consultant to create the interactive GIS map including the data. The GIS website will provide access to the raw data files and a template will be created for entering field data. A program called SiteTools will be created/modified that will allow the user to plot data files in assorted formats, merge data files of different types, build relationships between data types, export data to common formats (i.e. csv, xls), and develop correlations between the various field data. MDT's data management office has been consulted with regarding this research and will be coordinated with when developing the GIS map and data management program, to ensure compatibility with MDT systems and processes. The GIS website and SiteTools program will be maintained and available to the research team for the duration of the research project.

Montana Tech's research team will also include other data such as natural moisture, soil/rock type, geologic formation, unit weight to assist in developing the correlation with the subsurface soil and rock strength data. The data will be preprocessed and databases will be created. The results of the literature review and the preprocessed data to be used in the correlations will be discussed in the first quarterly meeting with the MDT staff, and after their approval, they will be reported as the "Task 1 report". We then proceed to the next steps. The literature review will be updated as the project proceeds and the complete version will be included in the final report.

Task 2: Investigating the correlations between MWD and the substrata strength using traditional methods

In the second stage of the research, traditional statistical approaches will be utilized to derive correlations between the MDT's MWD data and soil and rock layers' strengths. Effects of individual parameters as well as compound parameters on the correlations will be investigated. This step not only helps to understand the behavior of MWD data but also enables us to compare the results with results of previous work especially the work done by the Florida Department of Transportation and University of Florida (Rodgers et al. 2018a, 2018b, 2019, 2020; McVay and Rodgers 2020).

The results of task 2, i.e., the correlations developed based on the traditional methods, will be discussed in the second quarterly meeting with MDT staff. After their approval, and any required modifications, the results of task 2 will be reported as the “Task 2 report”. We then continue expanding the database. It is expected that more data will become available over the period of this project. The correlations will be reexamined and updated, and new correlations will be developed, if necessary, as more data become available. A complete set of correlations will be included in the final report.

Task 3: Development of Final Deliverables

According to the MDT guidelines, a three-month period is allocated for the final report comment/revision cycle. After this cycle and receiving all the comments, a “future steps, next phase small scale experiments, and future implementation discussion” meeting will be held with the MDT staff before the final report is submitted. After this meeting, the final report will be prepared and submitted to MDT.

A project summary report and an implementation report will also be prepared and submitted to the MDT. A performance measures report will be prepared if a B/C and ROI can be calculated.

The outcomes of task 2 will likely be simple equations that will be included in the reports. A short data help and user's guide explaining how to use developed correlations will be prepared. If necessary, a training session will be scheduled by the research team for the MDT staff. A project webinar will also be held where the outcomes of the project will be discussed. Finally, a project poster will be prepared and submitted to the MDT.

INTELLECTUAL PROPERTY

Ownership and Intellectual Property terms will be outlined in the contract between the Montana Department of Transportation and Montana Technological University upon acceptance of this proposal.

MDT AND TECHNICAL PANEL INVOLVEMENT

Creating the databases and developing correlations between MWD data and subsurface properties (tasks 1, 2, and 3) requires access to the MDT's MWD data, as well as CPT, VST, PMT, SPT, geophysics, in-situ and laboratory obtained soil and rock shear strength testing data. The PI has been in contact with the MDT staff (listed below) regarding this study and confirmed that the data mentioned above can be provided by the MDT Staff.

The mentioned MDT staff will lend their experience to the PI to interpret and analyze the input data mentioned above when needed. The PI will have Quarterly Progress Meetings with the MDT staff and they will also assist us in reviewing the deliverables.

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PRODUCTS

Project deliverables will include:

1. Monthly progress reports during meetings.
2. Quarterly written progress report.
3. Final report with a cover photo
4. Future steps, next phase small scale experiments and future implementation discussion meeting
5. Final presentation/Project Webinar
6. Project Poster
7. Project summary report
8. Implementation Report
   This report summarizes the results after the final Presentation/Implementation Meeting and will include implementation recommendations
9. Performance Measures Report

RISKS

Traditional correlation methods have been successfully used in the past, to correlate drilling data to some other desired outcomes. For example, there was a study with the intent to measure residual gas contents in coal seams. Considering the effectiveness of current correlations in use and the experience of the investigators, we think this project is feasible with a very good probability of success and with minimal risk.

IMPLEMENTATION

The results of this study will be 1) an interactive GIS-based map with the MWD data as well as strength data at different projects site and 2) correlations between MWD data and strength properties of soils and rock layers encountered at multiple MDT project sites. Geotechnical and Pavement Bureau of MDT would logically be responsible for applying the research results.

SCHEDULE

Table 1. Project Time Schedule

Task	2022				2023				2024			
	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12
1- Organization & preprocessing of data												
Task 1 report												
2- Correlations based on traditional methods												
Task 2 report												
3- Preparing the final deliverables												
Draft of the Final written report												
Final report comment/revision cycle												
The Final written report												
Project Summary Report												
Implementation Report												
Performance Measures Report												
Final presentation/Webinar/Poster												

Quarterly Progress Meeting/Reports

Deliverable Due Dates

Future steps, next phase small scale experiments, and future implementation discussion meeting

BUDGET

This project will be funded by the Montana Department of Transportation (MDT). The total cost of the project is **$103,553.67**, which is summarized in Table 2. The cost includes all allocated research staff time and other anticipated expenses. Travel has not been included because communication with MDT is to be done remotely in response to COVID-19 concerns. This budget includes $15,000 for consultant PMT testing and $4000 for expendable supply including a research license for MATLAB software. Table 3 shows the budget itemized by task.

Table 2. Detailed Project Budget

Labor Expenses							
Person	**Role**	**Total Hours**	**Hourly Wage Rate**	**Total Wages**	**Hourly Benefit Rate**	**Total Benefits**	**Total Cost**
Curtis Link	PI	75	$52.23	$3,917.25	$18.28	$1,371.04	$5,288.29
David Barrick, P.E.	Researcher	1,000	$22.00	$22,000.00	$1.28	$1,280.00	$23.280.00
Indirect Cost @ 33.5% MTDC:							$25,985.38
Total Labor Cost:							$54,553.67
Other Direct Expenses							
		Subcontractor: Drill Data Maps (Task 1)					$30,000
		Mapes In-Situ, LLC					$15,000
		In-State Travel					$0
		Expendable Supplies					$4,000
		Total Project Cost:					**$103,553.67**

Table 3. Task Budget

	Task Breakout
Item	**Total**
Task 1	$55,010.00
Task 2 & Task 3	$48,543.67
Total:	**$103,553.67**

STAFFING

The research team is comprised of the Principal Investigator (PI) Dr. Curtis Link, along with David Barrick, P.E. and PhD graduate student as research assistant. Short biographies of the PI and graduate student are provided below.

Curtis Link, PhD is professor emeritus of Geophysical Engineering at Montana Tech. He received the BA in physics from University of Iowa, BS in Geophysical Engineering from Montana Tech and PhD in geophysics from University of Houston. He started as Geophysical Engineering faculty at Montana Tech in 1994 and served as Director of Freshman Engineering from 2014 to 2018. His research interests include seismic methods for oil exploration, shallow seismic methods for environmental and geotechnical applications, machine learning methods in geoscience and shallow geophysical methods for site characterization. He has published in numerous journals and conference proceedings and been part of several funded research projects. A full resume is included.

Dr. Link will be responsible for most of the work in the report, including the literature review and initial data correlations. He will closely supervise the PhD student during the duration of the project. The graduate student will develop correlations under the supervision of Dr. Link.

David Barrick, P.E. is a Geotechnical Engineer with Dowl in Helena, Montana. David is responsible for geotechnical investigations and recommendations including deep and shallow foundations for structures, highway bridges, transmission towers, embankment dams, electrical substations, pavements, and municipal utility lines. He has performed geotechnical investigations consisting of logging for hollow-stem auger and rock core drilling throughout the state of Montana and the western United States for the past 16 years. David obtained his Bachelor of Science degree in General Engineering-Civil Option from Montana Technological University in 2005 and his Master of Science degree in Geological Engineering from Montana Technological University in 2022. David is a Professional Engineer in the State of Montana (#17401) and State of Idaho (#16989).

FACILITIES

The MWD data collection, as well as CPT, VST, PMT SPT, geophysics, in-situ, and laboratory obtained soil and rock shear strength testing data will be conducted on selected MDT project sites. Most of the data analyses and correlations will be conducted at Montana Technological University using MATLAB or Python.

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Education

PH.D. | 1993 | UNIVERSITY OF HOUSTON

- Geophysics

B.S. | 1985 | MONTANA TECH

- Geophysical Engineering

B.A. | 1971 | UNIVERSITY OF IOWA

- Physics
- Minor: Mathematics
- Related coursework: Secondary teaching certification

Skills & Abilities

ADMINISTRATION

- Department head geophysical engineering
- Director Freshman Engineering Program
- Associate Dean of Outreach

TEACHING

- Introductory physics for engineers
- Engineering thermodynamics
- Geophysical engineering courses
- FE exam preparation course: thermodynamics

INDUSTRY

- Seismic data processing for oil exploration
- Seismic data collection for oil: land and marine
- Unexploded ordnance (UXO) cleanup: magnetics geophysics
- Geophysical consulting: oil and gas, mining, geotechnical, water

RESEARCH

- Federal grants: DOE, NSF, DOD, NASA, Department of State, NIOSH/CDC
- State of Montana grants: MBRCT, SBIR/STTR
- Other: Trout Unlimited, Bureau of Land Management - Montana

Experience

ASSOCIATE DEAN/OUTREACH | MONTANA TECH | 2019 - PRESENT

· Work with Dean of School of Mines and Engineering in an outreach environment to recruit engineering students to Montana Tech

DIRECTOR FRESHMAN ENGINEERING PROGRAM | MONTANA TECH | 2014 - 2018

· Designed, developed, and implemented a Freshman Engineering Program to provide common basis for all engineering majors at Montana Tech

PROFESSOR/CHAIR | MONTANA TECH | 1999 - 2013

· Full professor and "intermittent" department head of Geophysical Engineering. Recruited students, obtained student funding, maintained "garage full" of equipment, supported and obtained software for students and research, maintained and established industry relationships for student support, research, and job placement. Obtained DOD funding for state-of-the-art digital seismic recording system.

ASSOCIATE PROFESSOR | MONTANA TECH | 1997-1999

· Participated in DOE and DOD research projects, established neural network class and continued implementation of neural networks into research.

ASSISTANT PROFESSOR | MONTANA TECH | 1994-1997

· Principal participant in large DOE grant for reservoir characterization using neural network analysis.

RESEARCH ASSISTANT | UNIVERSITY OF HOUSTON| 1990-1993

· Graduate research assistant – crosswell seismic tomography for reservoir characterization – DOE grant.

SEISMIC DATA PROCESSOR | HALLIBURTON GEOPHYSICAL | 1988-1990

· Processed seismic data in Houston office.

SEISMIC DATA ACQUISITION | GSI/HALLIBURTON | 1985-1988

· Collected land and marine seismic data offshore/onshore China and Thailand

Honors and Awards

NOMINATION FOR DISTINGUISHED RESEARCH

· 2003, 2005, 2007, 2008, 2010, 2012

ROSE AND ANNA BUSCH FACULTY ACHIEVEMENT AWARD

· 2002, 2005, 2010, 2013

Publications

Colin A. Zelt1, Seth Haines2, Michael H. Powers3, Jacob Sheehan4, Siegfried Rohdewald5, Curtis Link6, Koichi Hayashi7, Don Zhao8, Hua-wei Zhou9, Bethany L. Burton3, Uni K. Petersen10, Nedra D. Bonal11 and William E. Doll12, 2013, Blind Test of Methods for Obtaining 2-D Near-Surface Seismic Velocity Models from First-Arrival Traveltimes,, *Journal of Engineering and Environmental Geophysics,* 2013, 18, 3, 183-194.

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