MONTANA
Department of Transportation
Research

ORGANIZATION AND ANALYSIS OF MEASUREMENT WHILE DRILLING (MWD) DATA

FHWA/MT-25-001/10118-877

Final Report

February 2025

prepared for

THE STATE OF MONTANA DEPARTMENT OF TRANSPORTATION

in cooperation with

THE U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

February 2025

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/MT-25-001/10118-877	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Organization and Analysis of Measurement While Drilling (MWD) Data		**5. Report Date** February 2025 **6. Performing Organization Code**
7. Author(s) Curtis A. Link, Ph.D. (https://orcid.org/0009-0006-2927-9481) David J. Barrick, P.E. (https://orcid.org/0009-0000-4577-9386)		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Montana Technological University 1300 West Park Street Butte, MT 59701		**10. Work Unit No.** **11. Contract or Grant No.** **MDT Project # 10118-877**
12. Sponsoring Agency Name and Address Research Programs Montana Department of Transportation (SPR) 2701 Prospect Avenue PO Box 201001		**13. Type of Report and Period Covered** Final Report (August 2022 – March 2025) **14. Sponsoring Agency Code** 5401

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. This report can be found at https://www.mdt.mt.gov/research/projects/mwd.aspx DOI: https://doi.org/10.21949/1529565.

Recommended Citation: Link, C, Barrick, D. (2025). Organization and Analysis of Measurement While Drilling (MWD) Data: Final Report. (FHWA/MT-25-001/10118-877). Helena, MT: Montana Department of Transportation. https://doi.org/10.21949/1529565.

16. Abstract

The scope of the MDT funded research project highlighted collection and organization of data onto a portal, data review and quality control and analysis of relationships between MWD drilling parameters and rock properties. Our initial approach was investigation of traditional linear correlations between individual MWD drilling parameters and rock properties such as SPT blow count for hollow stem auger data and UCS or unit weight for rock core data. In addition to individual MWD data types (depth, rotation rate, rotation torque, down pressure and advance rate) we also included the calculated compound parameter specific energy. Based on weak, single parameter, linear correlation results using MWD data from multiple boreholes, we extended our correlation analysis to exponential fitting with no improvement in correlations. To further investigate correlations, we implemented a multiple linear regression (MLR) approach using all possible combinations of the six inputs. Correlation results improved for a number of combinations of inputs but still resulted in weak predictive models. Finally, because of poor linear correlation model predictive results, we turned to a nonlinear approach by implementing a feedforward neural network. The neural network (NN) approach investigated all combinations of MWD drilling parameters as inputs, used one hidden layer with varying numbers of neurons, and a single neuron output layer for predicting either SPT blow count, UCS or unit weight. Using a nonlinear approach greatly improved the predictive power of the MWD inputs for rock properties. Based on our data investigation and analysis results, we suggest that a viable MWD program adhere to a set of guidelines developed from experience and other researchers input that insure a consistent, repeatable drilling methodology with close attention to real-time data quality control.

17. Key Words MWD, regression analysis, geotechnical engineering, neural networks, multiple parameter linear correlation	**18. Distribution Statement** No restrictions.		
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 122	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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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

NN: Neural Network

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. Summary

The scope of the MDT funded research project highlighted collection and organization of data onto a portal, data review and quality control and analysis of relationships between MWD drilling parameters and rock properties. Our initial approach was investigation of traditional linear correlations between individual MWD drilling parameters and rock properties such as SPT blow count for hollow stem auger data and UCS or unit weight for rock core data. In addition to individual MWD data types (depth, rotation rate, rotation torque, down pressure and advance rate) we also included the calculated compound parameter specific energy.

We experimented with smoothing of MWD drilling data prior to analysis. Correlation results using smoothed or unsmoothed data were similar so we chose to use unsmoothed MWD data for analysis results presented here.

Based on weak, single parameter, linear correlation results using MWD data from multiple boreholes, we extended our correlation analysis to exponential fitting with no improvement in correlations. To further investigate correlations, we implemented a multiple linear regression (MLR) approach using all possible combinations of the six inputs. Correlation results improved for a number of combinations of inputs but still resulted in weak predictive models. Finally, because of poor linear correlation model predictive results, we turned to a nonlinear approach by implementing a feedforward neural network. The neural network (NN) approach investigated all combinations of MWD drilling parameters as inputs, used one hidden layer with varying numbers of neurons, and a single neuron output layer for predicting either SPT blow count, UCS or unit weight. Using a nonlinear approach greatly improved the predictive power of the MWD inputs for rock properties.

Based on our data investigation and analysis results, we suggest that a viable MWD program adhere to a set of guidelines developed from experience and other researchers input that insure a consistent, repeatable drilling methodology with close attention to real-time data quality control.

2. Background

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.

2.1. 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 was 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 was 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.

3. MWD Data Collection and Organization

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 but mainly focused in eastern Montana. The standard set of data collected 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 from the data portal 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 from data portal showing location of MWD sites along Highway 200 used for analysis.

4. 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 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 investigate 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.

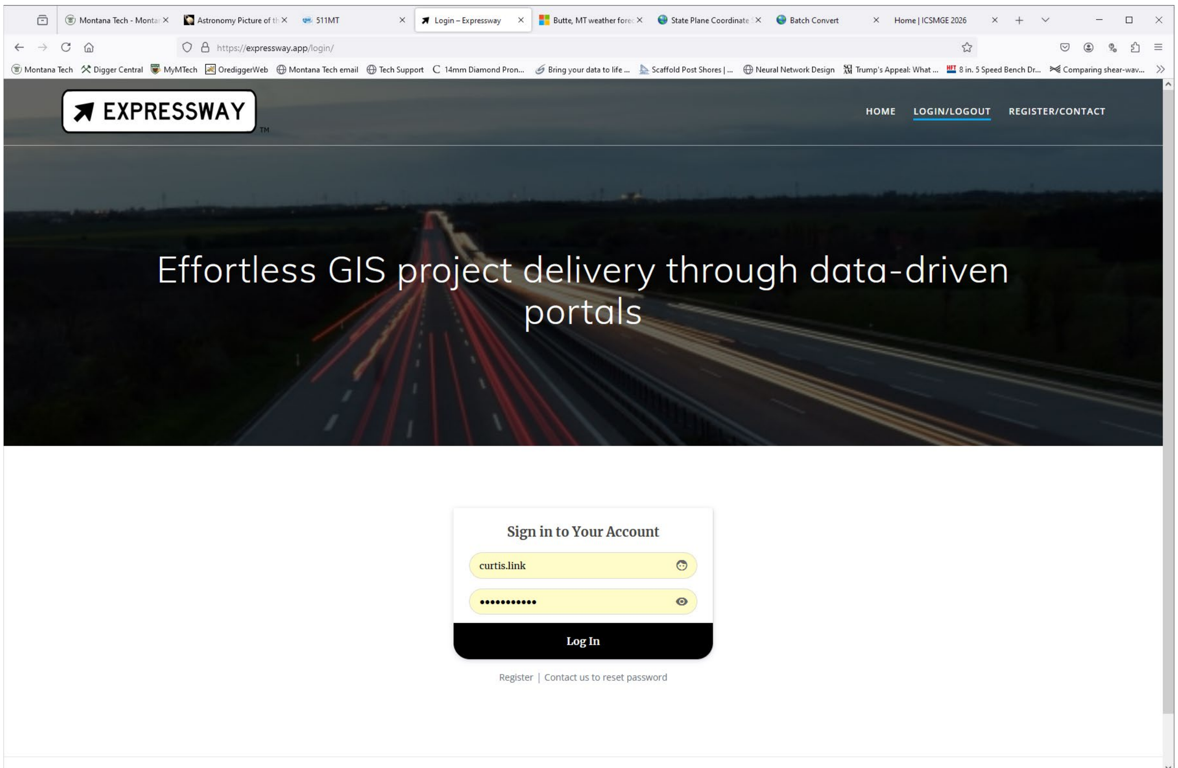


Figure 2. Login screen from Expressway Data Portal.

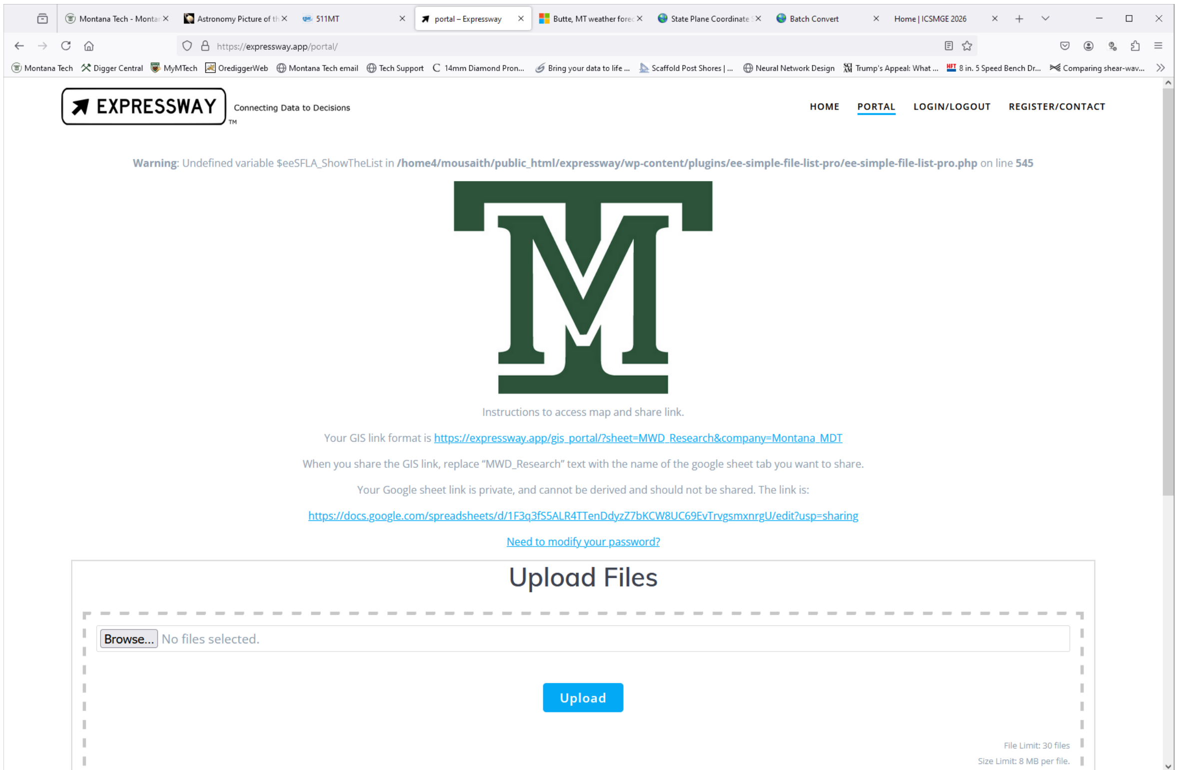


Figure 3. Access screen displaying active link (top link) for entering project site.

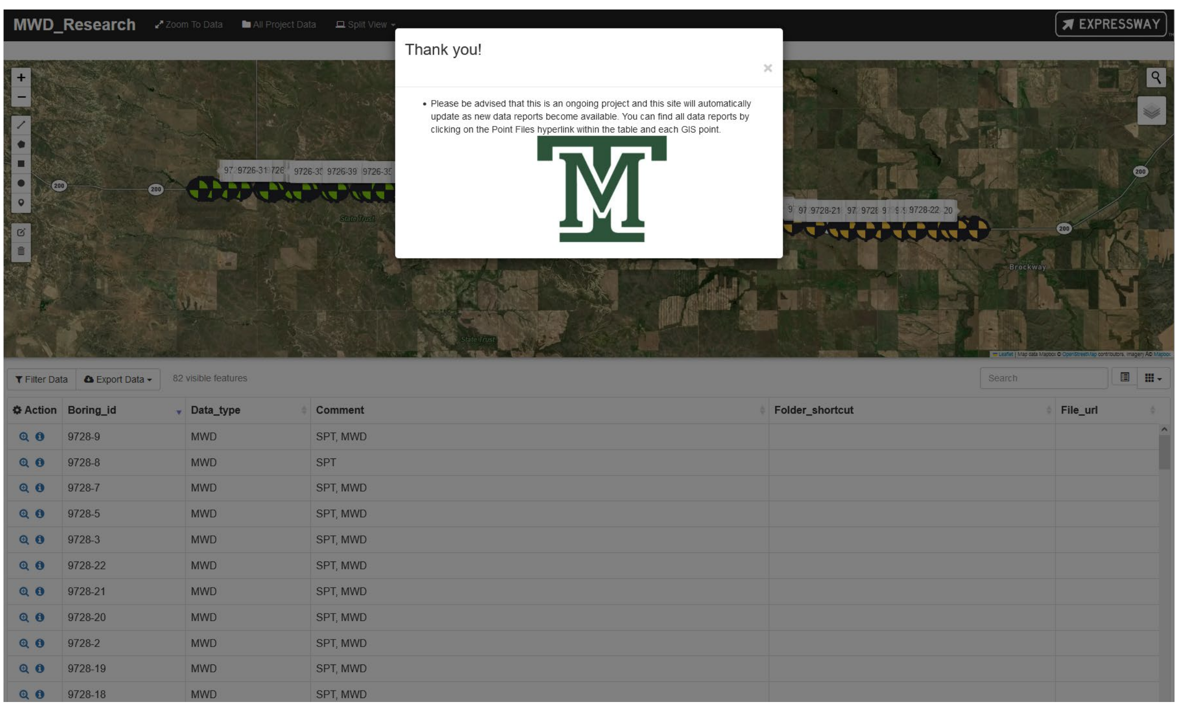


Figure 4. Splash screen indicating research project is ongoing and will be continually updated.

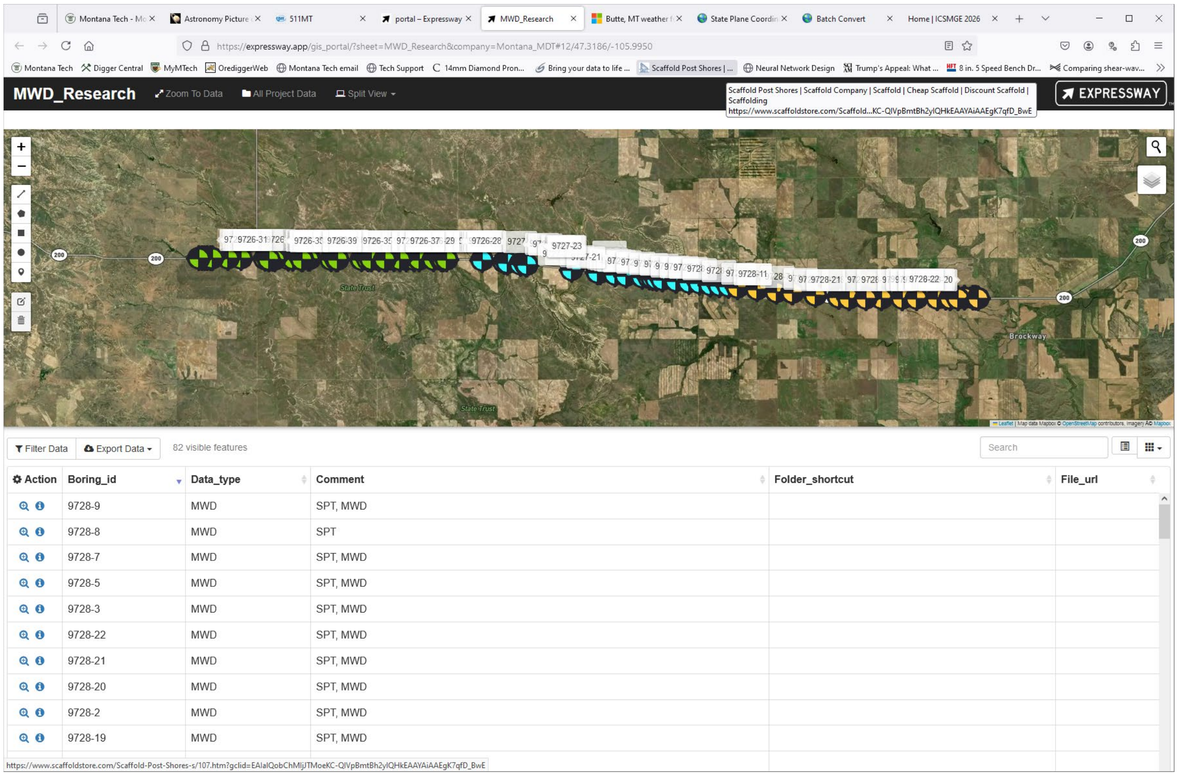


Figure 5. View of interactive map showing borehole numbering and list of data available for each borehole (scrollable).

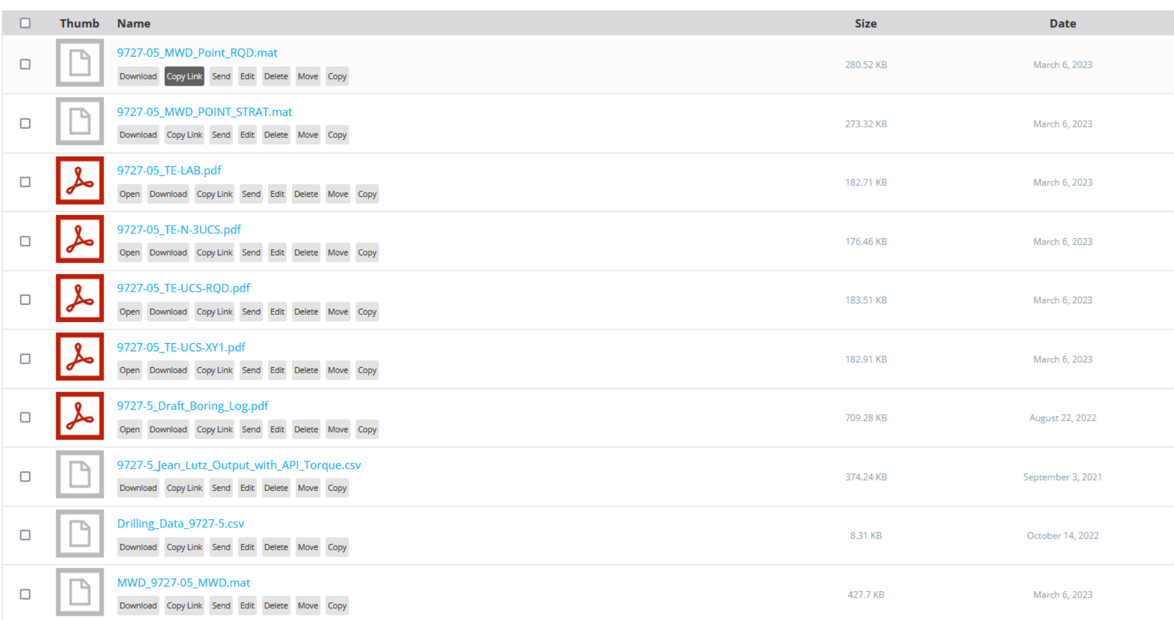


Figure 6. Example screen shot showing data types available for borehole 9727-05 with file size and upload date.

Table 1 shows 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 entries 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 used 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 drilling 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

5. 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.

5.1. 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 pronounced 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 measurement 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 especially 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 in Figure 7. 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 to 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.

5.2. 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.

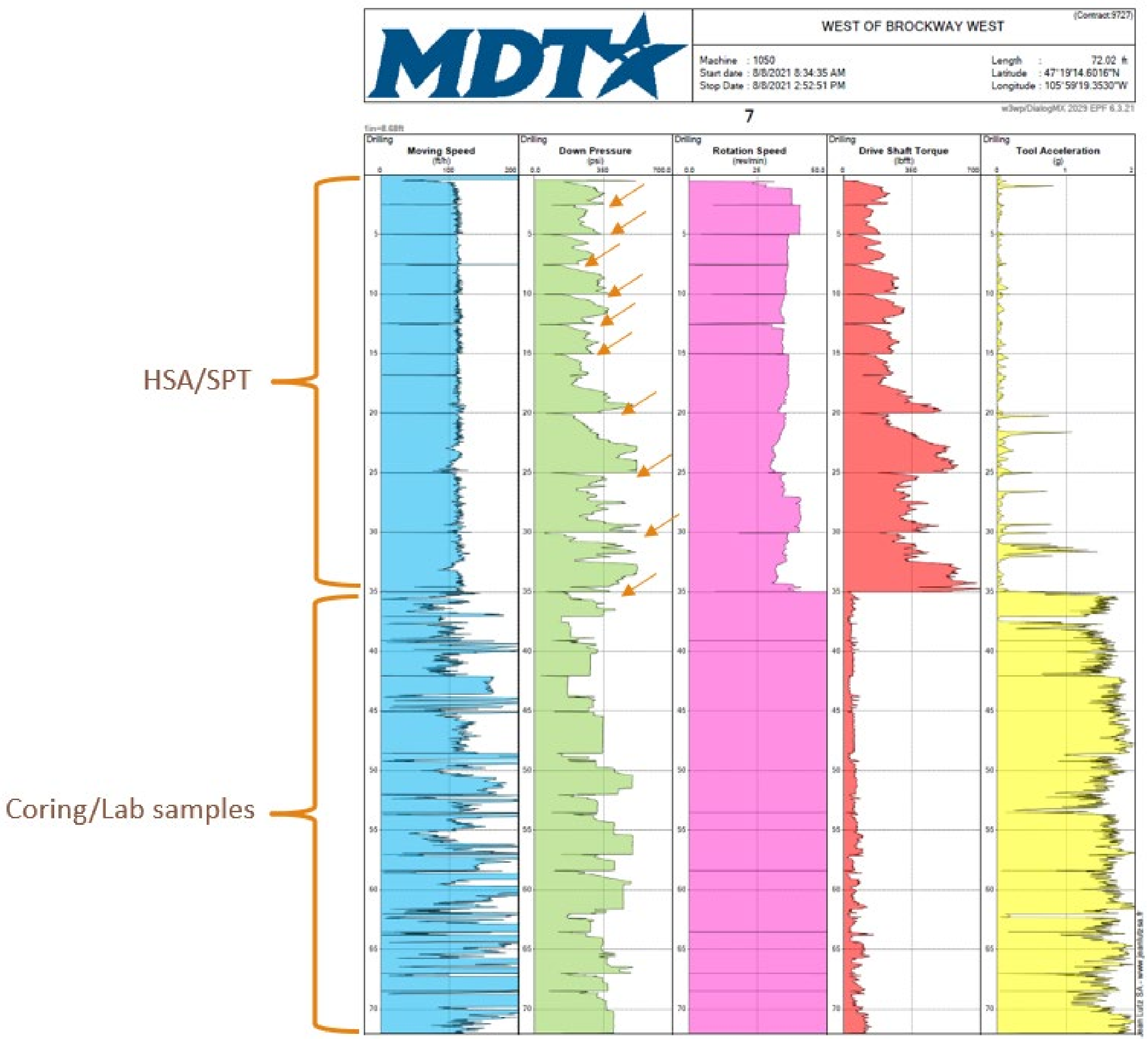


Figure 7. MWD data from borehole 9727-7 showing HSA depth section and rock coring section. Note arrows on Down Pressure plot (green) showing sharp drop in down pressure when drilling stopped.

6. Data Used for Analysis

6.1. GIS Portal Data

The full set of MWD data available on the GIS portal website is shown in Table 1. The data used for analysis are a subset from that list which contains Point Files. Point files contain the actual data files that can be used for analysis. This subset is shown as Table 4 below.

As can be seen in the Table 1 Comment column, not all MWD data Point Files contain the same types of data. Most of the borehole data sets contained SPT blow count data with MWD data from 0 to auger refusal depth (i.e., HSA data). Typical auger refusal depth in these eastern Montana IGM's was in the range of approximately 30 feet depth. A smaller set of boreholes contained lab measurements (i.e., UCS or unit weight) from HQ rock coring results below HSA refusal depth.

Our analysis approach took two forms: correlating SPT blow counts from HSA drilling with the various MWD measurements recorded and correlating UCS and unit weight from lab measurements with MWD measurements.

Table 5 lists the boreholes available for SPT blow count correlations and Table 6 lists the boreholes available for UCS and unit weight correlations.

Table 4. Subset of MWD data containing Point Files which can be used for analysis. List is organized by project number e.g., 9727-xx, 9726-xx.

Boring_id	Data_type	Comment	Folder_shortcut	File_url
9727-7	MWD	SPT, MWD, UCS	MWD_Research/9727000/9727-7	Point Files
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
9727-23	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
9727-13	MWD	SPT, MWD, VST	MWD_Research/9727000/9727-13	Point Files
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
9726-39	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-39	Point Files
9726-38	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-38	Point Files
9726-3	MWD	SPT, MWD	MWD_Research/9726000/9726-3	Point Files
9726-28	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-28	Point Files
9726-25	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-25	Point Files
9726-23	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-23	Point Files
9726-19	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-19	Point Files
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
9726-1	MWD	SPT, MWD	MWD_Research/9726000/9726-1	Point Files

Table 5. List of boreholes containing SPT blow count data and MWD data.

Boring_id	Data_type	Comment	Folder_shortcut	File_url
9727-7	MWD	SPT, MWD, UCS	MWD_Research/9727000/9727-7	Point Files
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
9727-13	MWD	SPT, MWD, VST	MWD_Research/9727000/9727-13	Point Files
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
9726-39	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-39	Point Files
9726-38	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-38	Point Files
9726-3	MWD	SPT, MWD	MWD_Research/9726000/9726-3	Point Files
9726-28	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-28	Point Files
9726-25	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-25	Point Files
9726-23	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-23	Point Files
9726-19	MWD	SPT, MWD, VST	MWD_Research/9726000/9726-19	Point Files
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
9726-1	MWD	SPT, MWD	MWD_Research/9726000/9726-1	Point Files

Table 6. List of boreholes containing UCS lab data and MWD data.

Boring_id	**Data_type**	**Comment**	**Folder_shortcut**	**File_url**
9727-7	MWD	SPT, MWD, UCS	MWD_Research/9727000/9727-7	Point Files
9727-5	MWD	SPT, MWD, VST, UCS	MWD_Research/9727000/9727-5	Point Files
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
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
9726-39	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-	Point

			39	Files
9726-38	MWD	SPT, MWD, UCS	MWD_Research/9726000/9726-38	Point Files
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

6.2. Hollow Stem Auger Data

Our goal for analysing hollow stem auger (HSA) data was to correlate relevant MWD parameters and/or compound parameters with borehole SPT blow count values. As detailed in the Task 1 report and also shown in Figure 7, plots of drilling data pulldown pressure exhibit a sharp decrease in pulldown pressure at intervals of 2.5 feet for depths 0 to 15 feet and at intervals of 5 feet for depths 15 to 35 feet. These sharp decreases represent drilling stops for auger section additions. Also, when drilling restarts, there is a delay before pulldown pressures reach full operating values again. These sharp decreases and ramping up of pressure prevent using the raw pulldown pressure values as recorded for analysis. Instead, we manually picked the peak pressure values prior to each auger change to correlate with SPT blow counts. Possible future work will consider an automated approach to identify these drilling discontinuities. After pre-processing, our analysis used data from 12 boreholes for a total of 64 data samples. Table 7 shows the final values used for correlation analysis of SPT blow count data with MWD data and the boreholes used.

6.3. HQ Rock Core Data

Our approach for analyzing MWD and rock coring lab data was exploring correlation of MWD parameters with UCS values as well as unit weight. After pre-processing, our data set for MWD and UCS consisted of data from six boreholes for a total of 117 data samples. The MWD parameters used were depth, pulldown pressure, rotation torque, rotation speed and rate of advance along with compound parameter specific energy. These parameters were extracted at the recorded depth and not averaged over an interval. Some rotation torque values from two boreholes were problematic and eliminated. All data were reviewed prior to correlation analysis. Table 8 shows the final values used for correlation analysis of UCS and unit weight with MWD data and their corresponding boreholes.

Table 7. Final spreadsheet containing SPT blow count data and MWD drilling data: Depth (feet), Peak Down Pressure (psi), Rotation Torque (lb-ft), Rotation Speed (rev/min), Moving Speed (ft/h), Specific Energy (ft-lb/ft^3).

Depth (feet)	Peak Down Pressure (psi)	Rotation Torque (lb-ft)	Rotation Speed (rev/min)	Moving Speed (ft/h)	Specific Energy (ftlb/ft^3)	Blows per foot
Borehole 9726-23						
7.5	467.49	247.05	37.43	137.7	67774.25926	4
10	450.74	324.94	36.67	126.06	65547.98104	3
12.5	440.63	370.5	37.42	131.06	64168.56046	4
15	419.98	520.62	36.83	138.64	61415.63133	3
20	415.87	400.05	45.43	127.84	60849.98759	4
25	513.23	632.83	37.96	127.4	75184.64617	9
30	804.32	594.79	49.65	134.24	117314.8978	60
35	794.73	526.88	46.77	121.55	115816.8401	91
40	570.77	640.23	46.98	136.89	83681.89695	75
Borehole 9727-7						
7.5	220.43	202.72	36.04	111.93	32184.85557	6
10	376.07	266.43	35.17	107.2	54747.23321	6
12.5	298.41	244.03	34.29	108.65	43493.66108	5
15	280.25	258.98	34.21	111.52	40895.10369	3
20	497.2	492.46	32.89	120.86	72506.20661	8
25	517.61	581.68	30.92	99.08	75767.64801	28
30	515.5	437.44	39.69	112.05	75283.46153	83
Borehole 9726-28						
7.5	259.84	151.28	40.92	110.46	37797.25311	5
12.5	533.74	640.08	29.08	126.77	77854.92391	28
15	476	647.53	37.72	83.5	70528.95132	38
20	705.45	648.86	44.75	100.65	103542.4518	41
Borehole 9726-13						
5	350.75	139.8	40.97	128.06	50811.50628	0.1
7.5	276.87	141.28	35.44	142.12	40108.3512	0.1
10	298.13	140.5	38.37	144.32	43184.20352	3
12.5	510.63	140.21	33.97	146.78	73750.9213	50
15	634	140.08	43.29	135.29	91600.16512	72
9726-38						
8	561.4	359.53	39.13	104.15	81758.22523	29
13	440.51	447.42	42.02	112.6	64566.462	29
18	470.77	220.77	43.16	109.2	68382.99438	38
23	465.7	536.39	43.83	95.21	68736.4159	39
28	515.35	307.87	42.04	135.12	74860.40573	43
9726-39						
5	194.48	61.5	45.51	105.32	28185.45452	2
10	328.7	125.24	50.14	103.47	47744.63163	3
15	793.36	447.95	47.89	112.87	115533.5794	48
20	540.21	403.28	48.01	113.02	78952.72847	51
9726-1						
7.5	526.88	106.45	62.66	72.56	76494.52049	5
10	580.02	185.79	63.42	66.83	84719.29748	3
12.5	617.27	274.52	52.08	71.99	90234.53378	4
15	566.93	104.47	73.27	76.23	82319.3147	5
20	661.37	59.96	61.87	80.7	95549.22621	18
25	679.6	222.2	40.37	43.64	99257.2378	21
9726-3						
7	560.24	125.27	23.69	160.17	80800.29346	16
9.5	626.96	518.06	29.18	127.28	91088.197	12
12	648.98	375.81	37.1	168.25	94015.45513	43
14.5	693.52	220.58	78.95	38.2	102960.4476	29
9726-19						
6.5	404.43	264.15	40.36	105.22	58925.47823	6
9	588.57	329.05	39.47	158.32	85310.754	26
11.5	863.35	327.16	36.84	152.53	124858.6092	38
9727-4						
5	358.81	244.58	36.05	60.07	52664.67309	4
10	504.75	385.17	36.09	146.29	73328.80947	9
12.5	493.54	455.63	31.77	63.06	72627.44843	16
15	511.83	436.66	32.03	102.16	74632.54059	14
20	378.93	372.13	33.1	63.85	55875.00158	30
9727-5						
5	381.1	150.84	35.38	106.36	55218.88967	5
7.5	262.81	146.09	36.66	114.4	38162.32287	4
10	249.28	119.97	36.36	123.15	36136.68418	5
12.5	203.45	114.52	36.47	124.83	29523.8415	13
15	217.78	180.73	36.86	122.83	31728.35333	11
20	537.37	587.29	39.18	114.2	78748.55616	40
9727-11	* No Point Files					
5	237.41	132.18	34.99	94.66	34518.59048	4
7.5	260.05	149.79	36.48	123.65	37747.0821	2
10	200.78	114.91	36.86	126.96	29138.70796	0.1
12.5	268.16	271.26	33.54	122.27	39119.97411	21
15	508.96	438.04	33.07	92.59	74351.90989	36
20	516.51	569.86	36.65	119.97	75558.78014	54

Table 8. Final spreadsheet containing UCS and unit weight data and MWD drilling data: Depth (feet), Peak Down Pressure (psi), Rotation Torque (lb-ft), Rotation Speed (rev/min), Moving Speed (ft/h), Specific Energy (ft-lb/ft^3).

Depth (feet)	Peak Down Pressure (psi)	Rotation Torque (lb-ft)	Rotation Speed (rev/min)	Moving Speed (ft/h)	Specific Energy (ftlb/ft^3)	UCS (psi)	Unit Weight (pcf)
Borehole 9727-7							
36.75	350.81	41.22	331.86	113.24	54,224	202.3	114.9
39.45	307.77	58.23	333.33	105.69	49,954	62.12	106.4
41.05	281.31	47.08	334.18	118.73	44,575	122.8	111.7
44.55	295.8	67.52	312.19	33.85	61,704	189.4	110.6
46.15	346.5	48.6	313.91	134.07	53,388	196.1	109.9
50.95	494.44	66.37	339.15	164.45	75,400	23.21	106.3
54.25	351.9	66.03	329.4	110.27	56,726	11.03	104
Borehole 9726-12							
31.05	412.4	3	335.57	51.92	59,981	58.84	111.8
31.5	404.39	2.99	337.8	48.78	58,868	136.4	108.4
32.3	495.83	3.12	338.32	6.11	76,701	48.18	109.4
32.9	489.42	2.81	340.15	51.88	71,042	133	109
35.6	223.37	3.04	321.67	146.39	32,370	12.17	98.79
40.65	581.2	3.09	329.09	44.38	84,396	30	90.5
41.25	579.62	3.2	334.17	357.31	83,557	224.9	72.4
41.55	577.5	3.24	332.53	150.53	83,380	320.4	71.9
41.7	282.74	3.17	333.03	19.38	42,386	80.2	83.4
42.1	333.04	3.32	332.5	51.5	48,616	288.2	89.9
42.95	331.48	2.99	332.8	53.1	48,308	86.6	87.3
46.7	399.11	3.22	331.18	55.03	58,067	14.38	105.2
47.7	395.38	3.09	331.64	58.12	57,476	70.81	112.3
51.1	397.69	3.19	316.25	134.72	57,497	51.07	109.8
51.8	426.96	2.98	316.07	146.75	61,679	255	114.4
52.4	426.51	3.28	311.03	50.02	62,043	111.1	113.2
53.05	424.68	2.95	313.91	54.25	61,678	72.62	107.9
53.8	428.17	3.26	314.42	127.01	61,904	70.29	112.2
56	412.15	3.04	333.12	143.54	59,566	28.03	102.1
56.6	349.43	3.04	334.5	76.23	50,727	216	115
60.5	452.71	2.85	320.27	58.56	65,669	218.3	118.7
61.2	450.82	3.12	320.59	60.03	65,429	156.7	119.9
61.9	499.05	3.07	320.48	95.89	72,178	74.58	115.4
62.6	497.16	3.17	320.44	119.88	71,851	115.5	114.1
64.1	480.3	3.16	320.32	234.52	69,296	9.54	104.7
66.15	444.53	3.2	326.14	183.55	64,187	122	112.6
67	506.31	3.25	324.05	171.31	73,097	75.68	109.8
67.7	506.01	2.95	323.41	161.25	73,047	289.8	118.5
69	409.04	3.26	324.41	86.52	59,277	18.33	106
Borehole 9726-13							
30.15	264.22	40.69	331.84	24.85	54,722	49	105
31.8	418.93	40.66	332.26	215.15	62,253	27	107
32.7	521.15	40.56	307.74	59.55	81,478	58	112
38.6	421.69	40.62	331.05	78.41	65,986	233	112
40.6	419.84	40.91	340.43	70.59	66,511	219	117
41.4	414.97	40.64	340.62	46.82	68,828	141	114
42.1	412.4	40.68	340.89	77.53	64,874	101	114
42.7	409.52	40.55	340.55	53.05	66,959	145	117
43.4	565.96	40.64	339.41	87.47	86,337	200	119
44.05	604.44	40.53	339.93	86.49	91,928	102	118
44.8	412.55	40.61	341.42	59.78	66,524	400	119
50.4	404.37	40.47	340.1	76.48	63,752	25	106
51.9	407.56	40.75	340.9	180.42	61,051	26	116
52.8	412.18	40.8	340.96	88.08	64,200	105	115
53.55	184.56	40.64	344.82	15.87	53,673	70	113
9726-38							
33.75	422.96	67.13	252.84	58.7	69,779	83	116.3
34.4	414.67	63.34	253.51	35.83	73,465	445.4	97.1
34.7	410.71	59.36	253.62	24.91	77,688	259	71.8
35.1	407.56	65.27	253.31	34.9	73,226	437.1	75.9
35.3	406.24	63.9	253.17	8.7	115,560	547.1	70.3
35.45	403.23	57.35	254.18	28.3	73,872	351.1	87.3
36.75	392.66	52	255.98	10.82	94,294	119.6	124.5

37.75	330.02	58.74	256.03	30.16	62,825	54.01	122.2
40.25	299.77	39.59	241.95	79.49	46,865	44.01	106.3
41.25	182.48	43.68	248.57	131.81	28,805	206.7	115.4
44.75	282.83	57.53	247.9	29.37	55,628	64.25	114.5
45.25	275.93	39.73	249.87	28.83	50,301	43.85	111.8
46.25	314.54	58.92	247.79	42.76	55,771	78.84	114.8
46.75	313.06	58.28	247.65	43.69	55,218	104.2	112.6
47.25	295.02	56.86	248.37	41.51	52,923	42.26	116.7
48.25	302.84	84.34	263.2	41.01	60,219	41.95	117.8
48.75	305.03	75.37	263.69	49.58	56,225	62.72	119.8
49.75	304.45	70.53	263.71	55.34	54,154	67.43	118.8
50.25	299.34	66.55	264.33	58.99	52,256	161.9	125.4
50.75	295.33	55.84	264.21	82.04	48,046	188.1	121.8
9726-39							
22.25	247.96	95.08	259.51	44.83	52,596	37.14	106.8
24.4	345.15	100.05	259.79	49.95	65,670	462.5	76.6
24.6	343.74	98.94	259.96	50.88	65,011	582	74.3
24.85	343.65	98.68	259.81	52.56	64,454	608.9	71
25.1	328.93	120.32	211.87	70.42	58,474	535.4	77
25.4	336.04	103.54	274.75	47.25	66,865	448.5	72.7
25.65	324.01	105.7	274.73	37.69	70,300	383.7	73.7
26.1	300.01	94.89	246.47	35.04	63,683	8.86	105.2
33.75	313.84	95.54	273.81	104.61	52,867	40.68	112.1
34.25	312.21	92.27	273.71	83.77	54,210	59.2	114.8
36.25	301.52	96.03	247.93	66.38	54,425	228.3	114.7
36.75	287.41	92.08	233.03	53.85	53,615	298.7	116.6
46.75	114.01	83.51	258.49	119.81	21,946	133	120.7
9727-5							
27.5	309.82	23.1	308.49	293.16	45,360	20.69	102
31.05	390.17	28.64	320.65	81.02	59,663	58.84	111.8
31.5	501.63	28.5	321.01	62.44	76,731	136.4	108.4
32.3	497.46	43.73	318.9	108.74	75,570	48.18	109.4
32.9	496.55	47.45	319.17	86.83	76,855	133	109
34.8	416.58	27.37	321.1	88.55	63,033	61.03	105.9
35.6	376.6	17.98	311.46	343.41	54,731	12.17	98.79
40.65	407.35	19.53	331.05	76.56	61,250	30	90.5
41.25	550.38	47.52	329.22	49.37	88,979	224.9	72.4
41.55	549.05	49.69	328.51	64.98	86,772	320.4	71.9
41.7	548.73	49.09	329.22	64.61	86,693	80.2	83.4
42.1	593.61	39.34	328.69	65.55	91,533	288.2	89.9
42.95	593.65	51.83	328.44	63.29	93,739	86.6	87.3
46.7	273.51	33.11	339.74	82.42	43,574	14.38	105.2
47.7	308.07	39.68	338.67	82.78	49,344	70.81	112.3
48.5	323.19	35.73	337.89	140.34	49,179	95.77	108.5
51.1	309.73	43.84	342.17	90.17	49,706	51.01	109.8
51.8	314.32	42.55	342.99	89.46	50,268	255	114.4
52.4	304.12	25.44	343.77	81.47	47,087	111.1	113.2
53.05	171.96	31.79	344.09	114.22	27,701	72.62	107.9
53.8	309.11	34.15	342.67	108.05	47,835	70.29	112.2
56	307.45	52.14	266.73	169.6	46,789	28.03	120.1
56.6	285.88	35.24	267.9	54.24	46,508	216	115
57.4	399.29	53.27	339.43	83.6	64,135	165.4	110.5
60.5	318.01	35.21	318.5	55.79	51,962	218.3	118.7
61.2	481.6	56.24	316.23	69.08	77,251	156.7	119.9
61.9	496.43	57.89	316.48	85.58	78,055	74.58	115.4
62.6	497.85	51.31	318.46	47.43	82,262	155.5	114.1
64.1	419.97	72.15	315.82	83.63	68,837	9.54	104.7
66.15	275.99	25.77	336.15	62.08	44,025	122	112.6
67	397.53	51.49	333.58	75.21	64,252	75.68	109.8
67.7	352.6	35.51	334.8	53.36	57,611	289.8	118.5
69	273.08	25.61	344.21	74.34	42,962	18.33	106

7. 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).

7.1. 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:

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

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

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

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.

7.2. Final Data Assembly

The last step of data pre-processing 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 imported into the Matlab® based scripts developed by the research team.

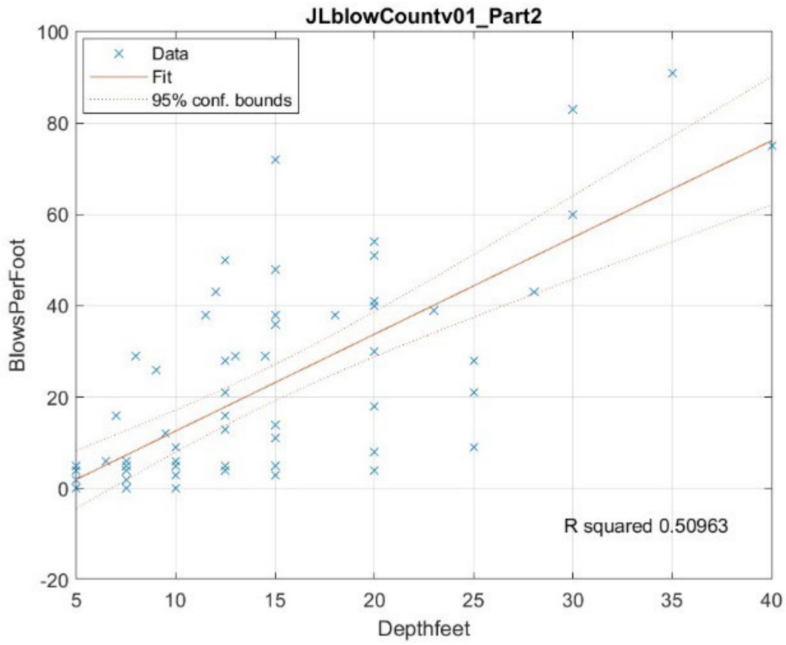
8. Analysis Results

8.1. Phase 1: Single Parameter Linear and Exponential Regression Modeling

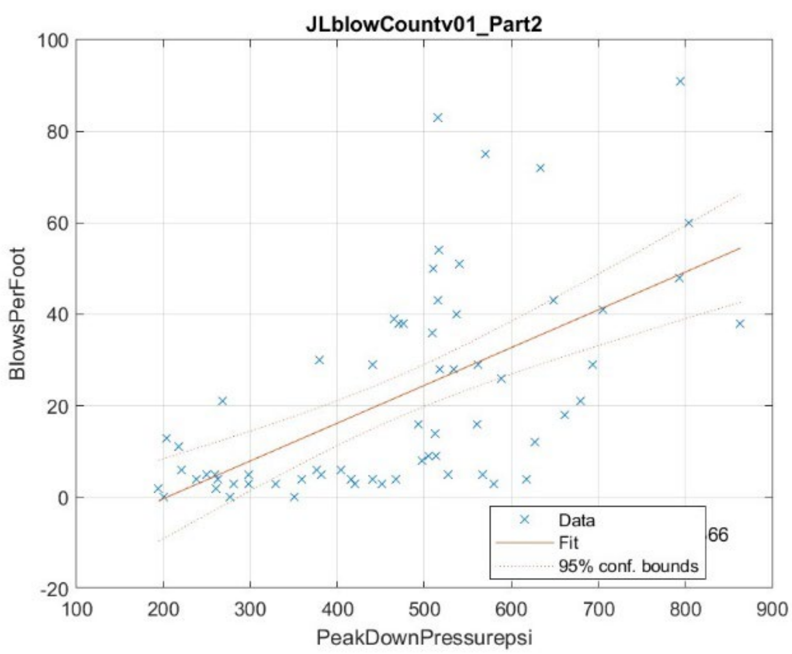
Initial analyses consisted of plotting target parameters (SPT blow count, UCS, and unit weight) against six individual MWD parameters: depth, down pressure, rotation torque, rotation speed, moving speed and the compound parameter specific energy. A best fit linear regression line was calculated and the Pearson correlation coefficient (R^2) recorded for each MWD parameter. We also explored correlation results using a best fit exponential curve and tabulated those R^2 values as well.

8.1.1. SPT Blow Count Correlations

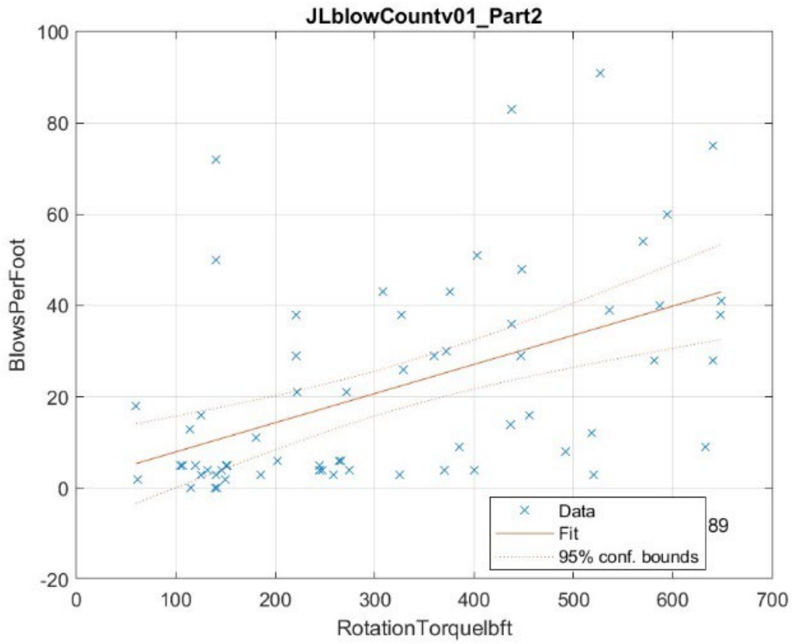
Figure 8 shows results for single parameter *linear* regression correlation for SPT blow counts. Figure 9 shows results for single parameter *exponential* fitting for SPT blow counts. R^2 values are tabulated and listed in Table 9.


JLblowCountv01_Part2
Data
Fit
95% conf. bounds
BlowsPerFoot
Depthfeet
R squared 0.50963
100
80
60
40
20
0
-20
5
10
15
20
25
30
35
40

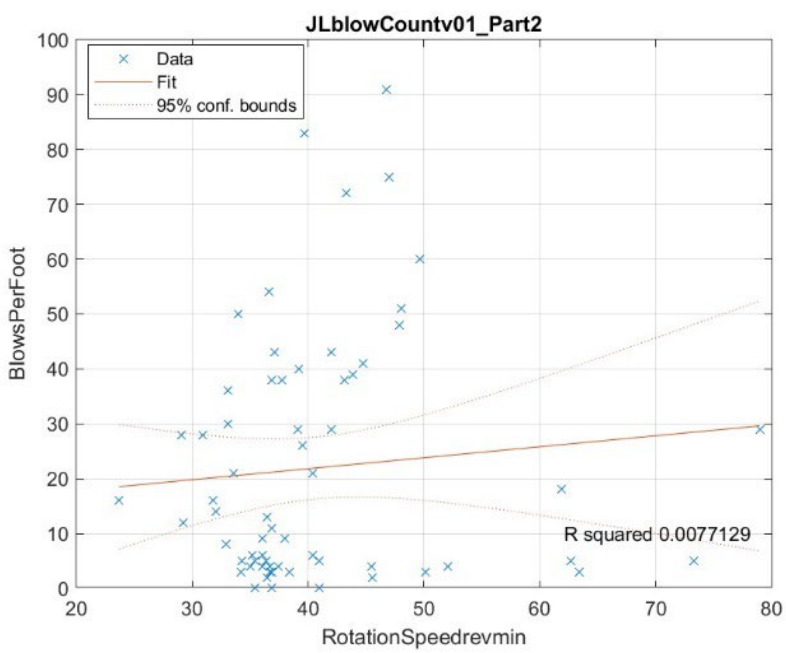
(a)


JLblowCountv01_Part2
Data
Fit
95% conf. bounds
66
BlowsPerFoot
PeakDownPressurepsi
100
80
60
40
20
0
-20
100
200
300
400
500
600
700
800
900

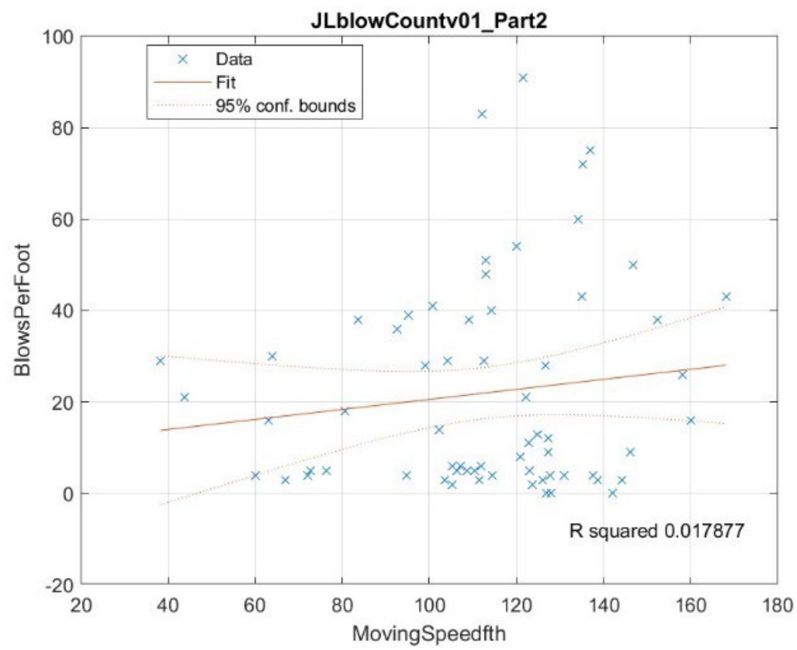
(b)


JLblowCountv01_Part2
BlowsPerFoot
RotationTorquelbft
Data
Fit
95% conf. bounds
89

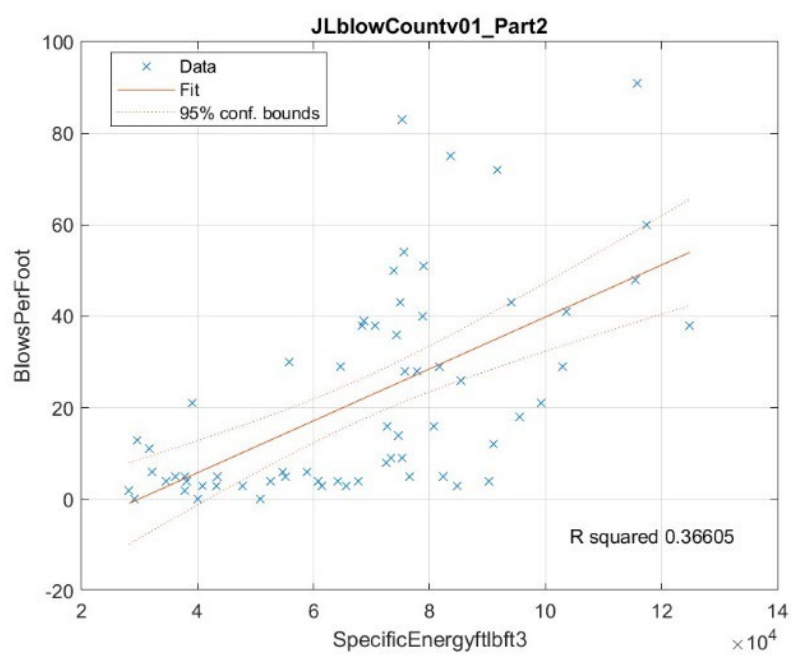
(c)


JLblowCountv01_Part2
BlowsPerFoot
RotationSpeedrevmin
Data
Fit
95% conf. bounds
R squared 0.0077129

(d)

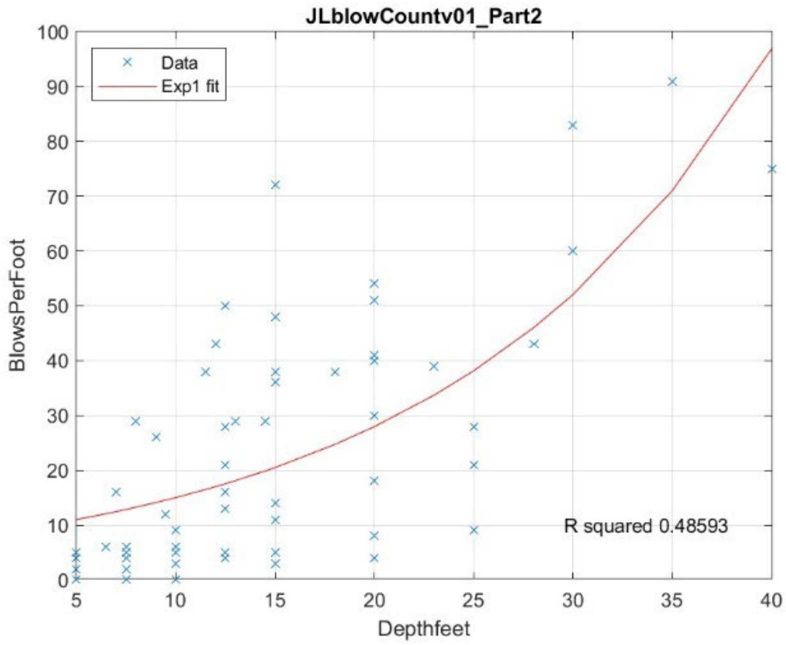


(e)

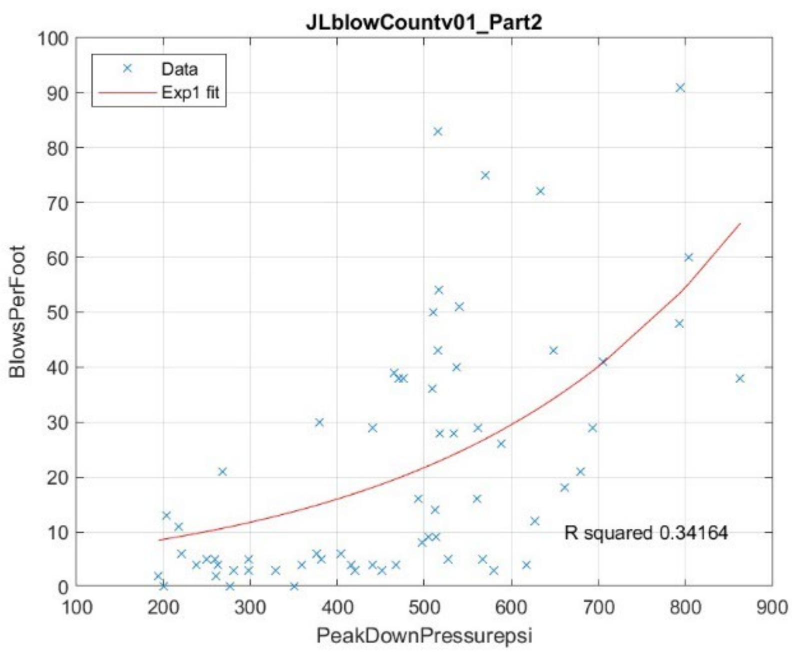


(f)

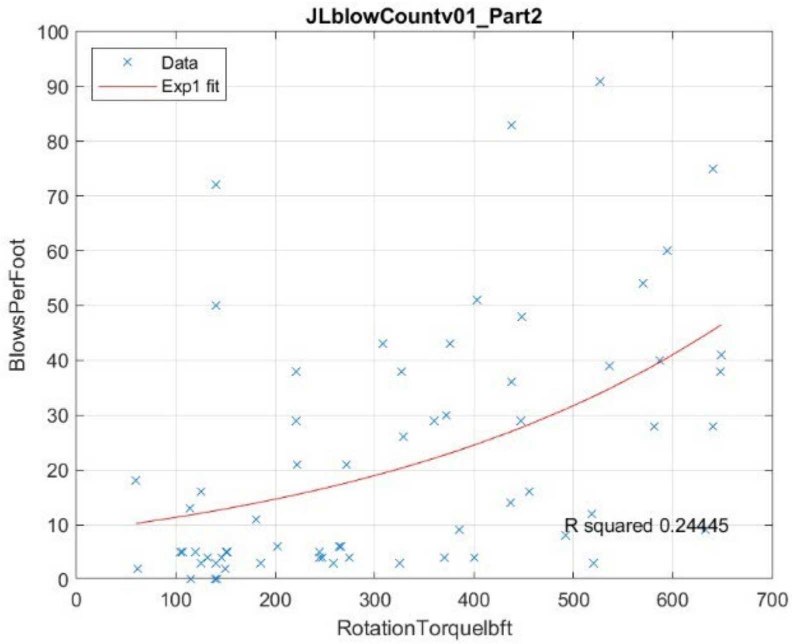
Figure 8. Single parameter linear regression correlation results for SPT blow counts versus (a) depth, (b) down pressure, (c) torque, (d) rotation speed (e) moving speed and(f) specific energy. R^2 values are tabulated in Table 9.


JLblowCountv01_Part2
Data
Exp1 fit
BlowsPerFoot
Depthfeet
R squared 0.48593
0
10
20
30
40
50
60
70
80
90
100
5
10
15
20
25
30
35
40

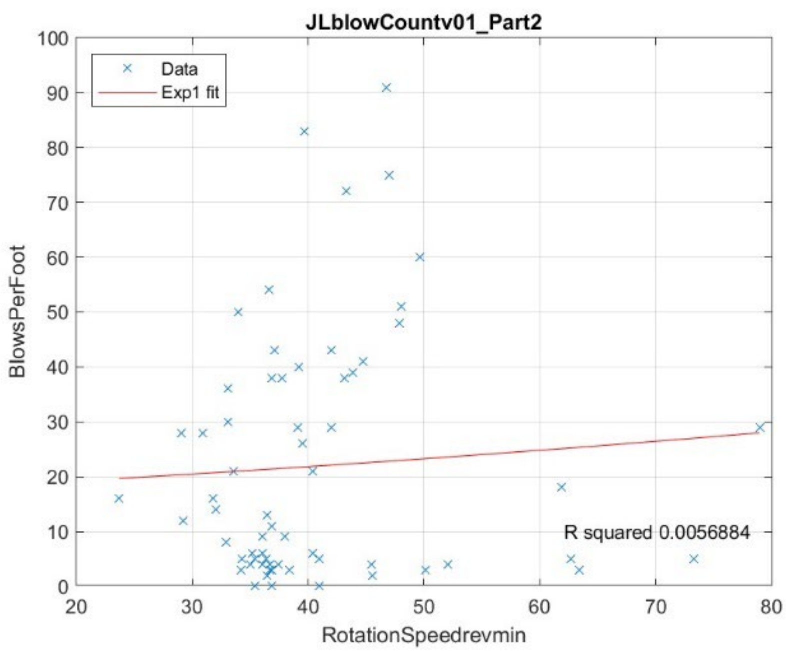
(a)


JLblowCountv01_Part2
Data
Exp1 fit
BlowsPerFoot
PeakDownPressurepsi
R squared 0.34164
0
10
20
30
40
50
60
70
80
90
100
100
200
300
400
500
600
700
800
900

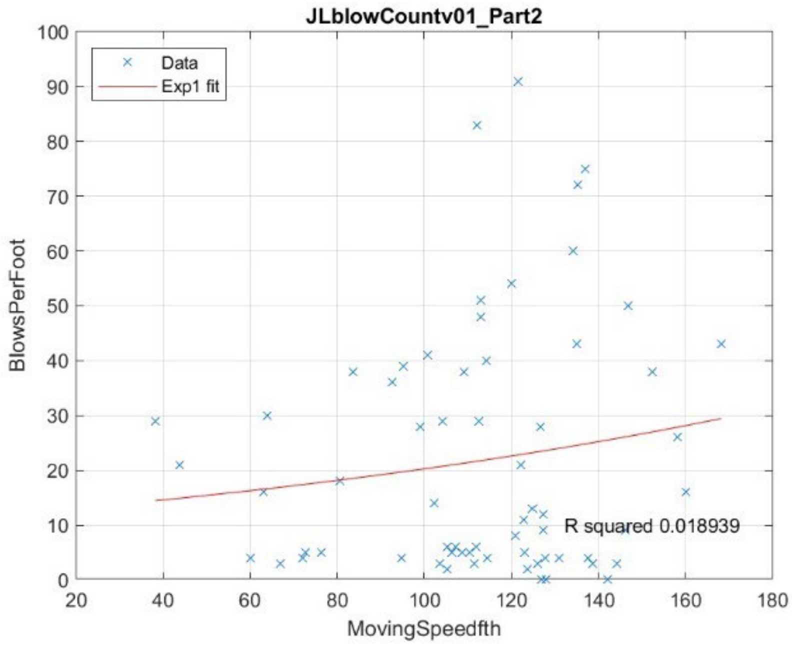
(b)


JLblowCountv01_Part2
Data
Exp1 fit
R squared 0.24445
BlowsPerFoot
RotationTorquelbft
0
10
20
30
40
50
60
70
80
90
100
100
200
300
400
500
600
700

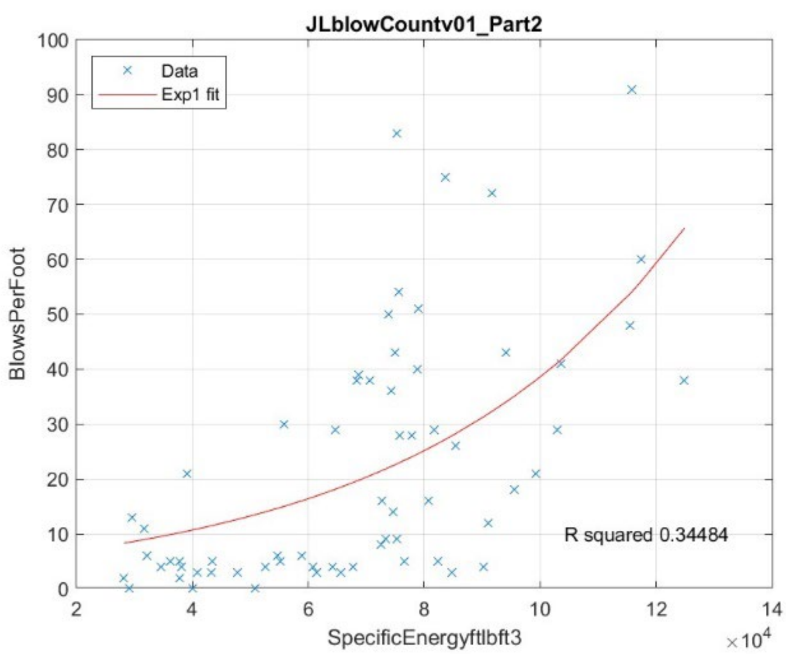
(c)


JLblowCountv01_Part2
Data
Exp1 fit
R squared 0.0056884
BlowsPerFoot
RotationSpeedrevmin
0
10
20
30
40
50
60
70
80
90
100
20
30
40
50
60
70
80

(d)



(e)



(f)

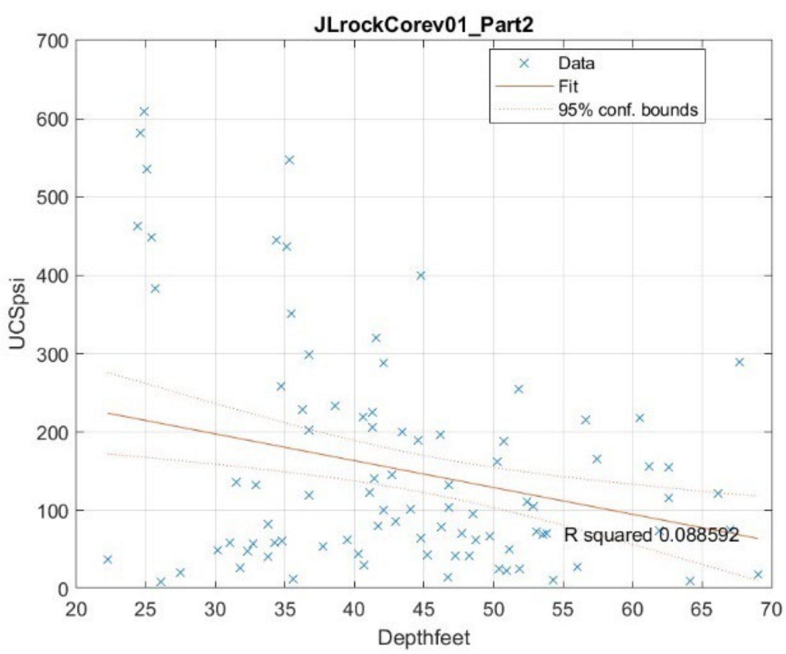
Figure 9. Single parameter exponential regression correlation results for SPT blow counts versus (a) depth, (b) down pressure, (c) torque, (d) rotation speed (e) moving speed and(f) specific energy. R^2 values are tabulated in Table 9.

Table 9. Tabulated R^2 values for single parameter linear and exponential fitting for SPT blow counts.

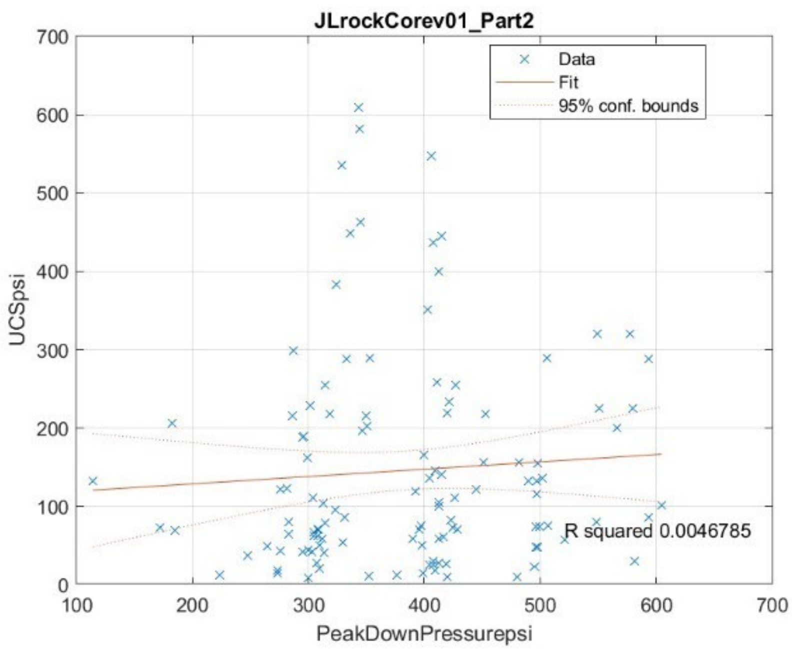
MWD parameter	Linear R^2	Exponential R^2
Depth	0.51	0.49
Down pressure	0.36	0.34
Rotation torque	0.25	0.24
Rotation speed	0.01	0.01
Moving speed	0.02	0.02
Specific energy	0.37	0.34

8.1.2. UCS Correlations

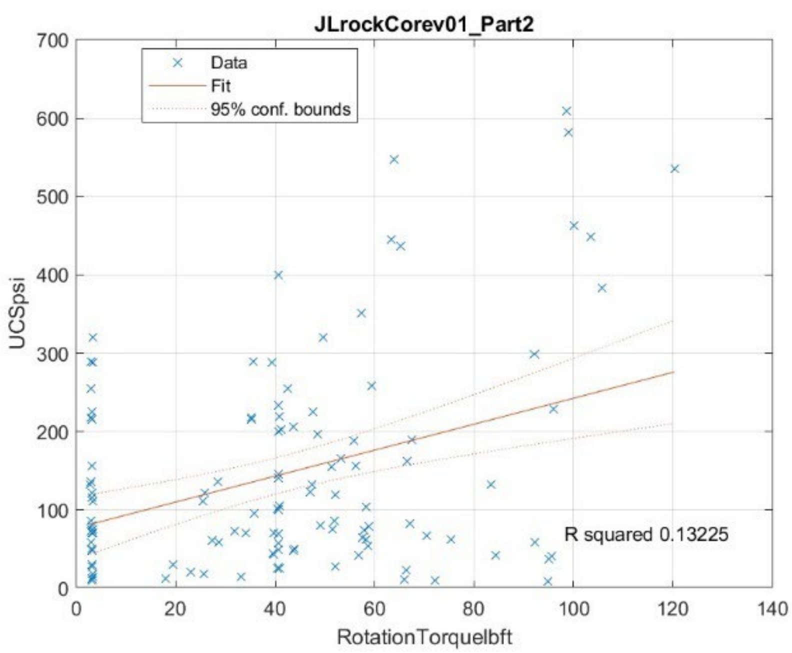
Figure 10 shows results for single parameter *linear* regression correlation for UCS. Figure 11 shows results for single parameter *exponential* fitting for UCS. R^2 values are tabulated and listed in Table 10.



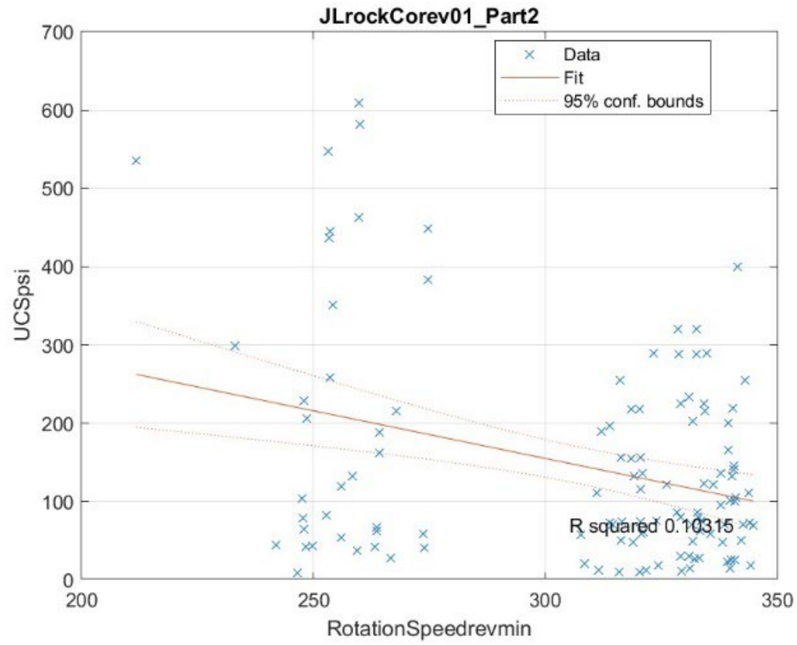
(a)


JLrockCorev01_Part2
Data
Fit
95% conf. bounds
R squared 0.0046785
UCSpsi
PeakDownPressurepsi
0
100
200
300
400
500
600
700

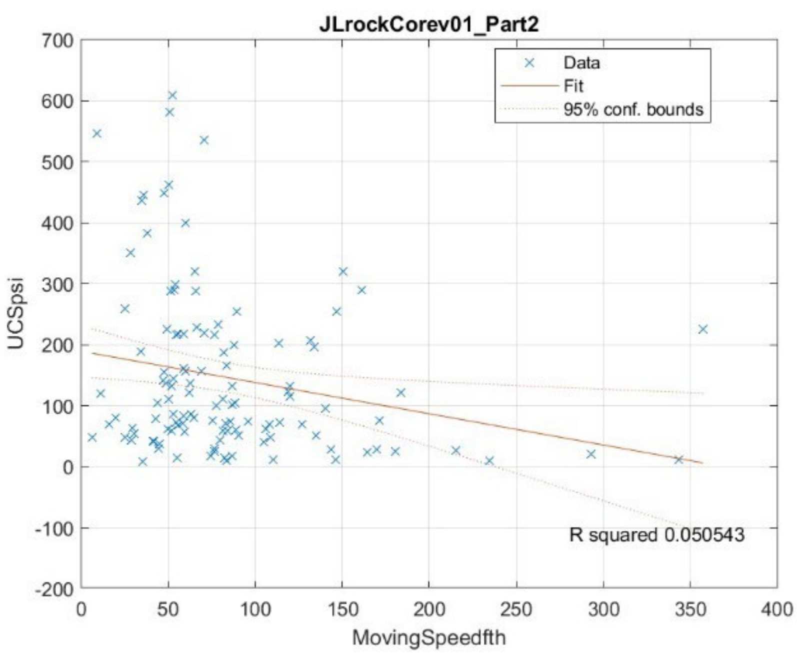
(b)


JLrockCorev01_Part2
Data
Fit
95% conf. bounds
R squared 0.13225
UCSpsi
RotationTorquelbft
0
20
40
60
80
100
120
140

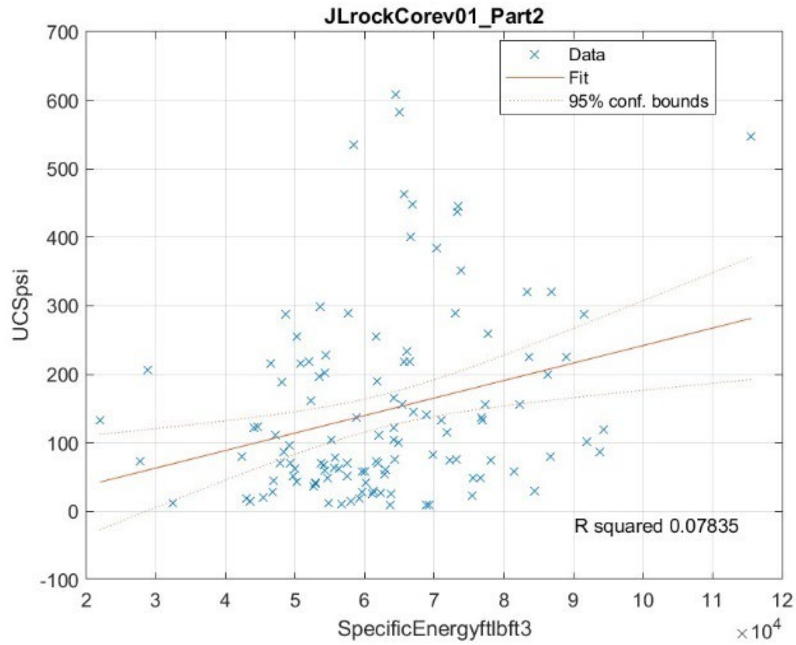
(c)


JLrockCorev01_Part2
Data
Fit
95% conf. bounds
R squared 0.10315
UCSpsi
RotationSpeedrevmin
0
100
200
300
400
500
600
700
200
250
300
350

(d)

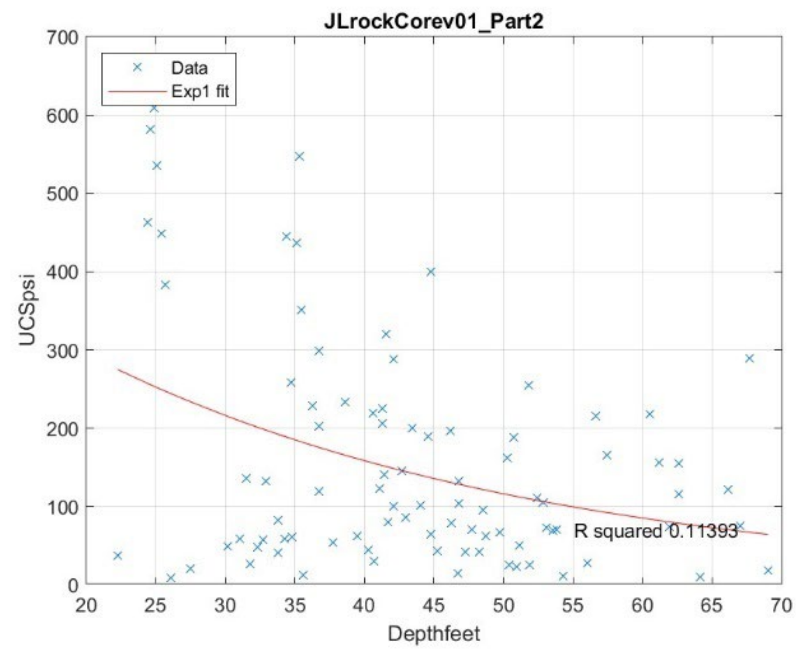

JLrockCorev01_Part2
Data
Fit
95% conf. bounds
R squared 0.050543
UCSpsi
MovingSpeedfth
-200
-100
0
100
200
300
400
500
600
700
0
50
100
150
200
250
300
350
400

(e)

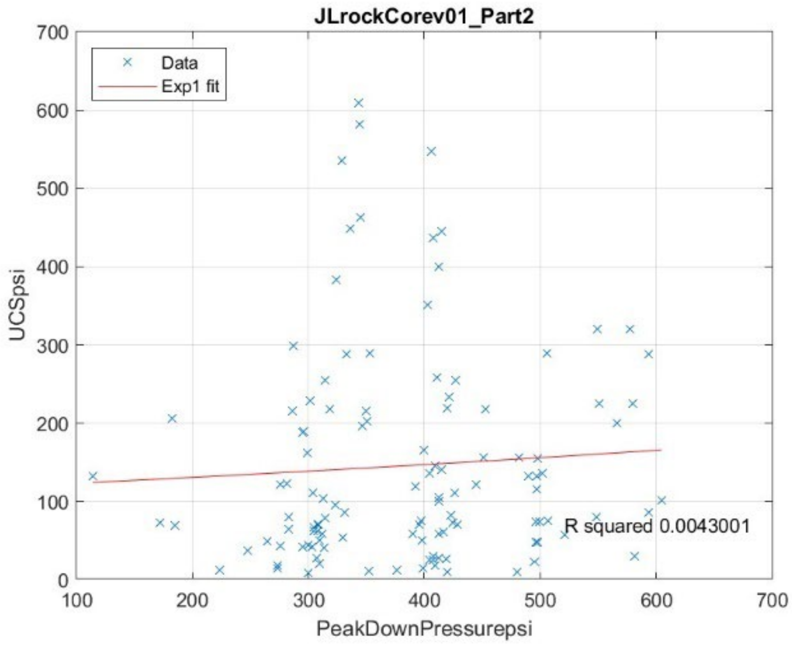


(f)

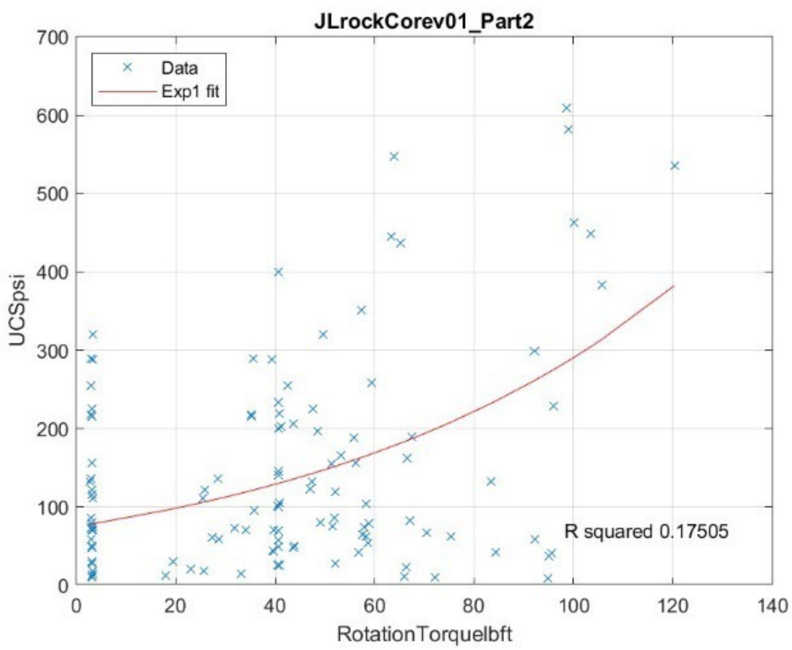
Figure 10. Single parameter linear regression correlation results for UCS versus (a) depth, (b) down pressure, (c) torque, (d) rotation speed (e) moving speed and(f) specific energy. R^2 values are tabulated in Table 10.



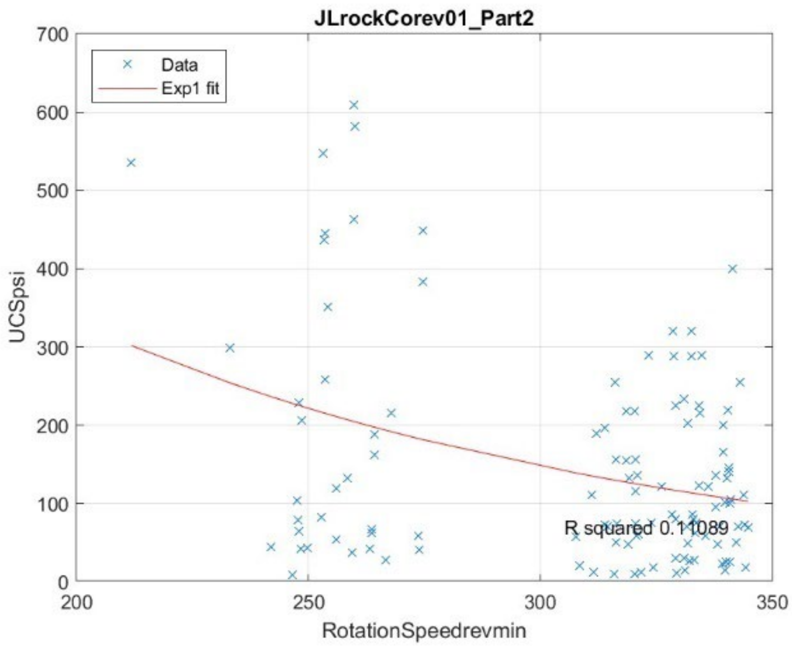
(a)


JLrockCorev01_Part2
Data
Exp1 fit
UCSpsi
PeakDownPressurepsi
R squared 0.0043001
700
600
500
400
300
200
100
0
100
200
300
400
500
600
700

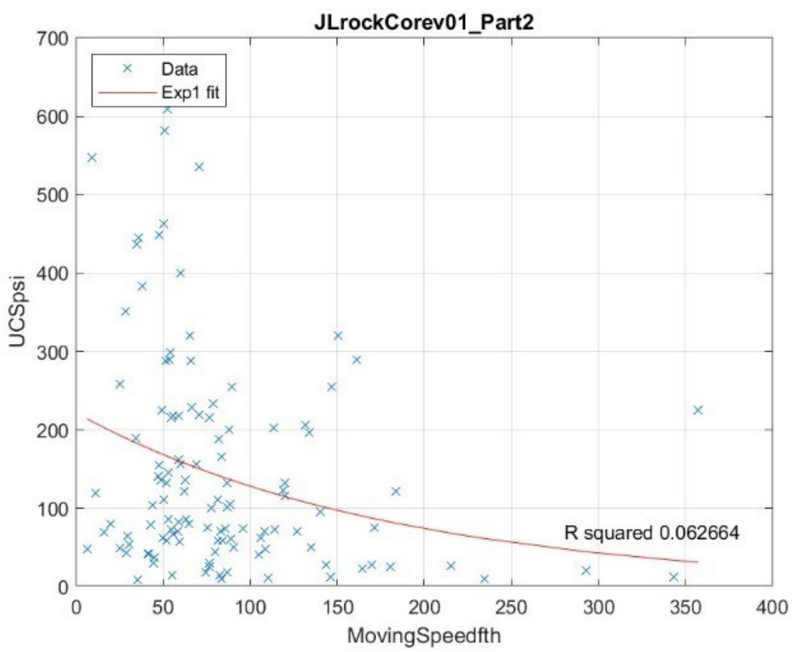
(b)


JLrockCorev01_Part2
Data
Exp1 fit
UCSpsi
RotationTorquelbft
R squared 0.17505
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140

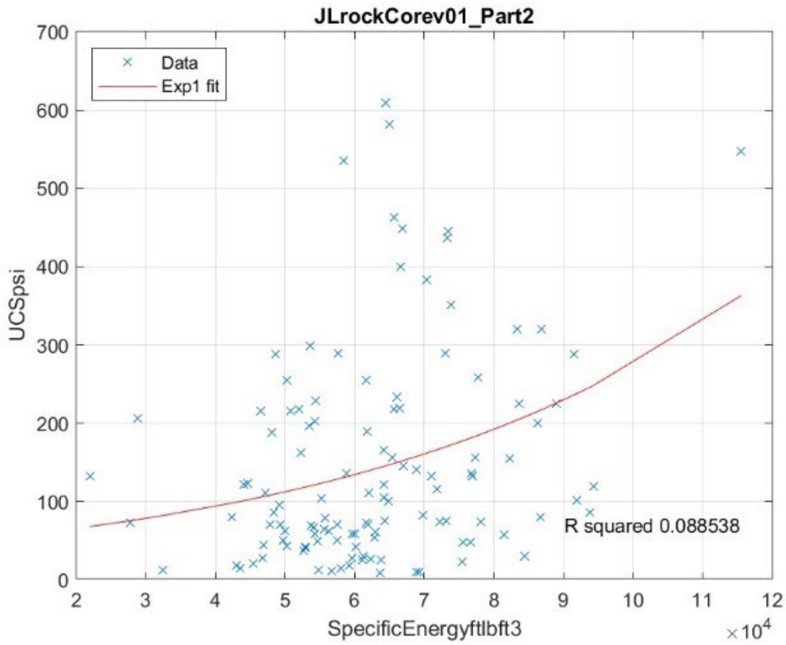
(c)


JLrockCorev01_Part2
Data
Exp1 fit
R squared 0.11089
UCSpsi
RotationSpeedrevmin
0
100
200
300
400
500
600
700
200
250
300
350

(d)


JLrockCorev01_Part2
Data
Exp1 fit
R squared 0.062664
UCSpsi
MovingSpeedfth
0
100
200
300
400
500
600
700
0
50
100
150
200
250
300
350
400

(e)



(f)

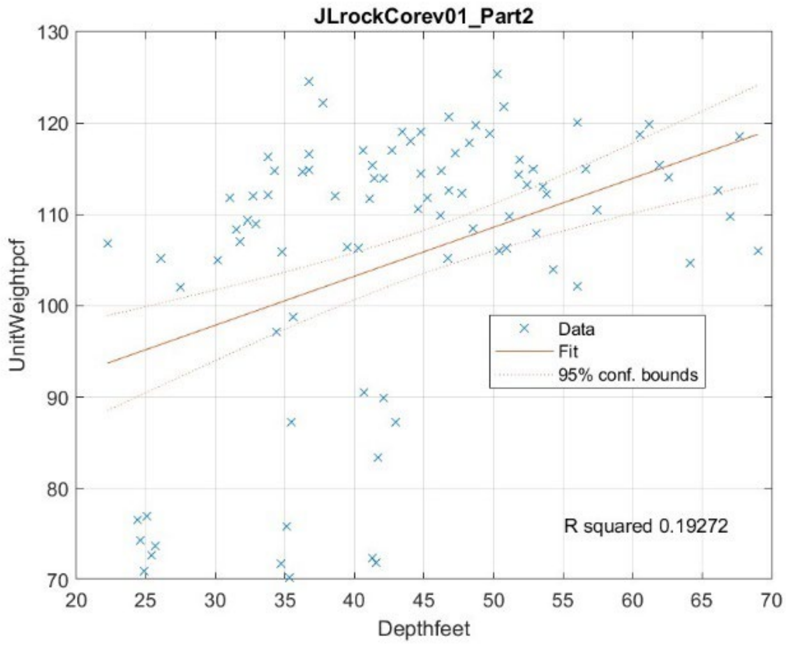
Figure 11. Single parameter exponential regression correlation results for UCS versus (a) depth, (b) down pressure, (c) torque, (d) rotation speed (e) moving speed and(f) specific energy. R^2 values are tabulated in Table 10.

Table 10. Tabulated R^2 values for single parameter linear and exponential fitting for UCS.

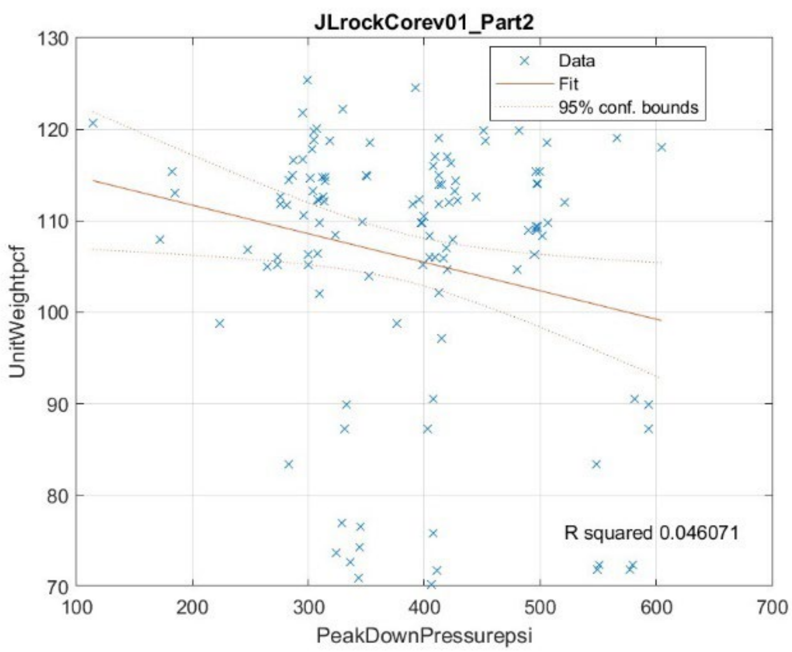
MWD parameter	Linear R^2	Exponential R^2
Depth	0.009	0.11
Down pressure	0.005	0.004
Rotation torque	0.13	0.18
Rotation speed	0.10	0.11
Moving speed	0.05	0.06
Specific energy	0.08	0.09

8.1.3. Unit Weight Correlations

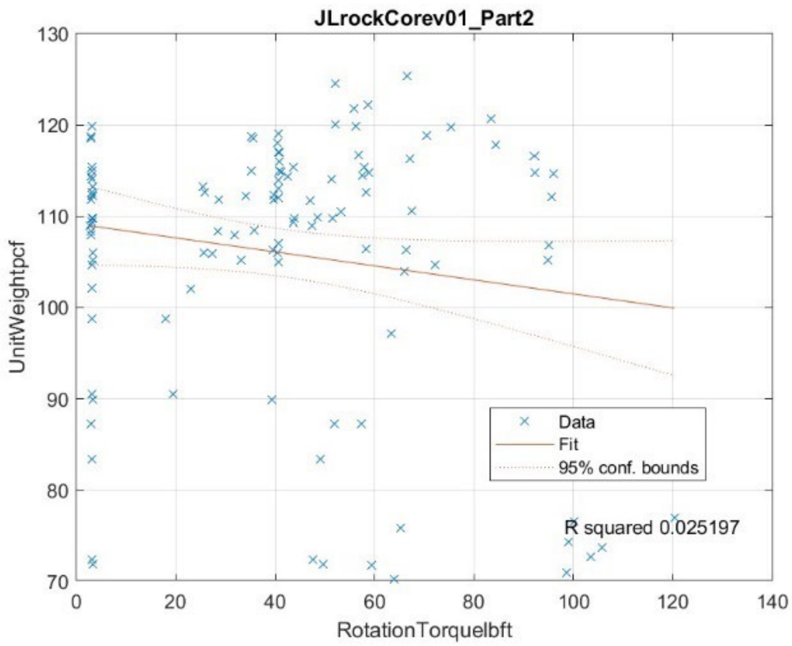
Figure 12 shows results for single parameter *linear* regression correlation for unit weight. Figure 13 shows results for single parameter *exponential* fitting for unit weight. R^2 values are tabulated and listed in Table 11


JLrockCorev01_Part2
UnitWeightpcf
Depthfeet
Data
Fit
95% conf. bounds
R squared 0.19272

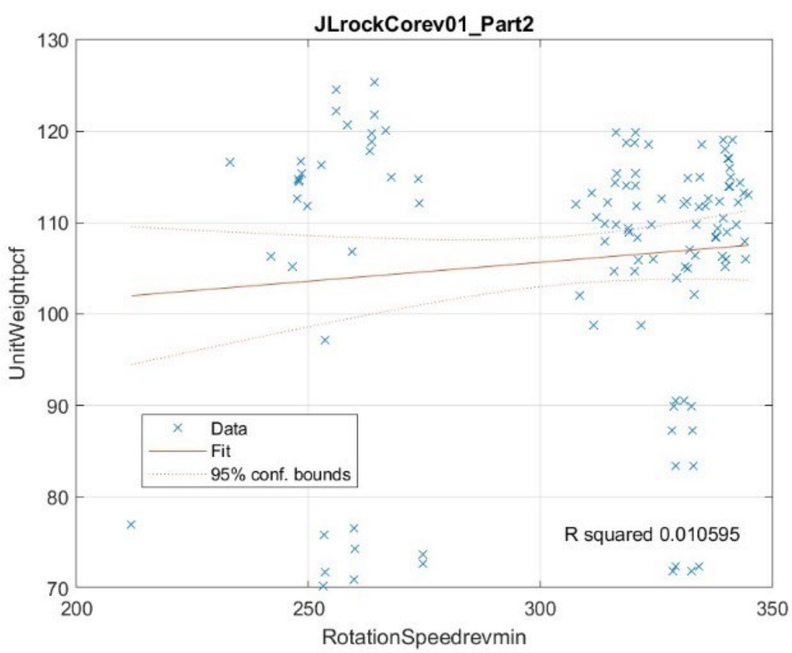
(a)


JLrockCorev01_Part2
UnitWeightpcf
PeakDownPressurepsi
Data
Fit
95% conf. bounds
R squared 0.046071

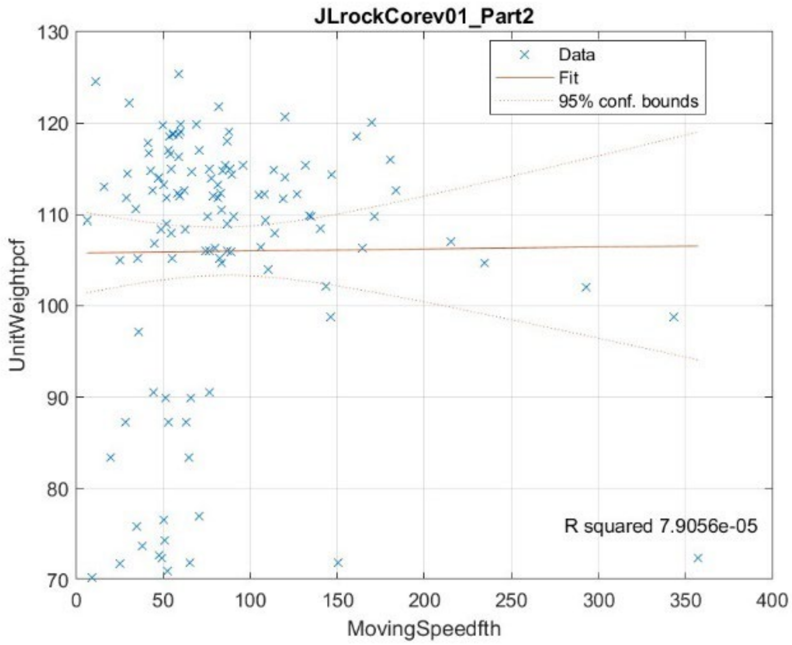
(b)


JLrockCorev01_Part2
UnitWeightpcf
RotationTorquelbft
Data
Fit
95% conf. bounds
R squared 0.025197
130
120
110
100
90
80
70
0
20
40
60
80
100
120
140

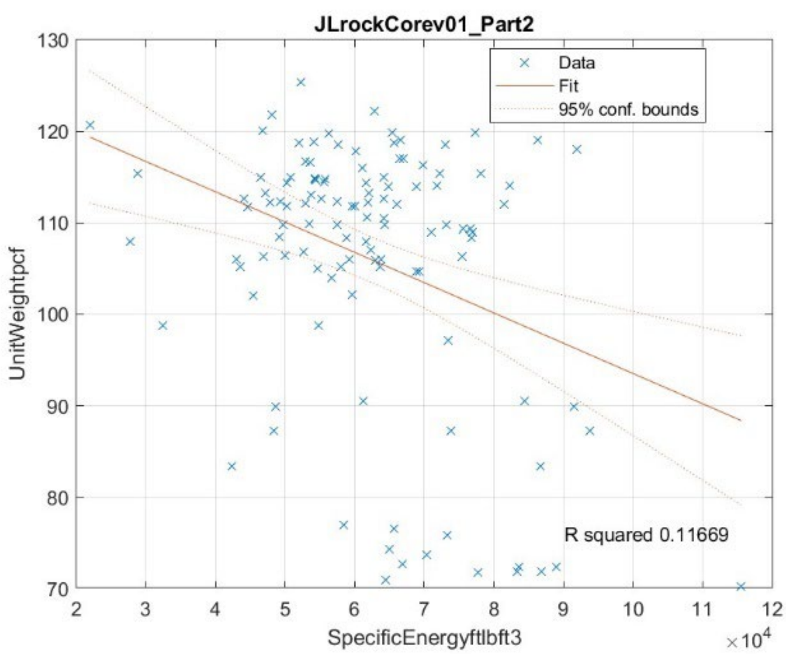
(c)


JLrockCorev01_Part2
UnitWeightpcf
RotationSpeedrevmin
Data
Fit
95% conf. bounds
R squared 0.010595
130
120
110
100
90
80
70
200
250
300
350

(d)

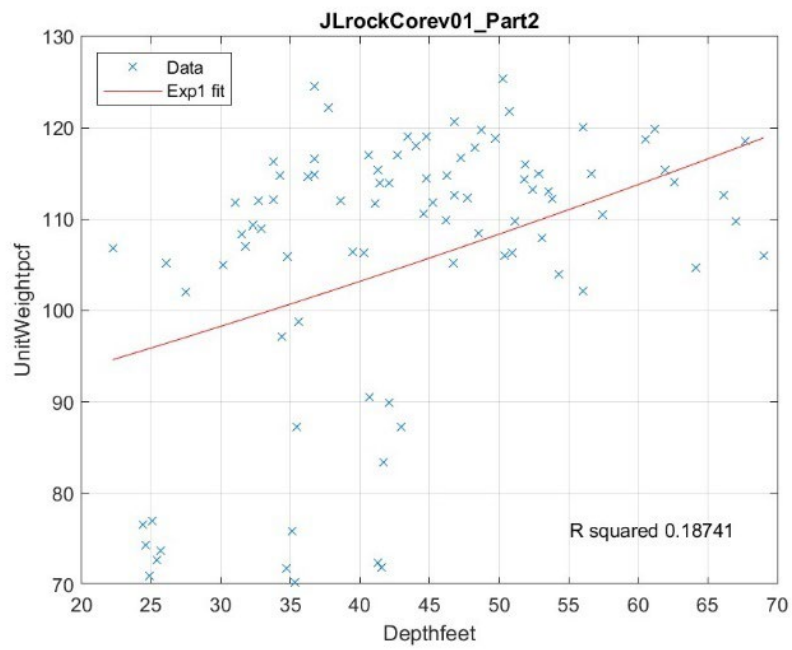


(e)

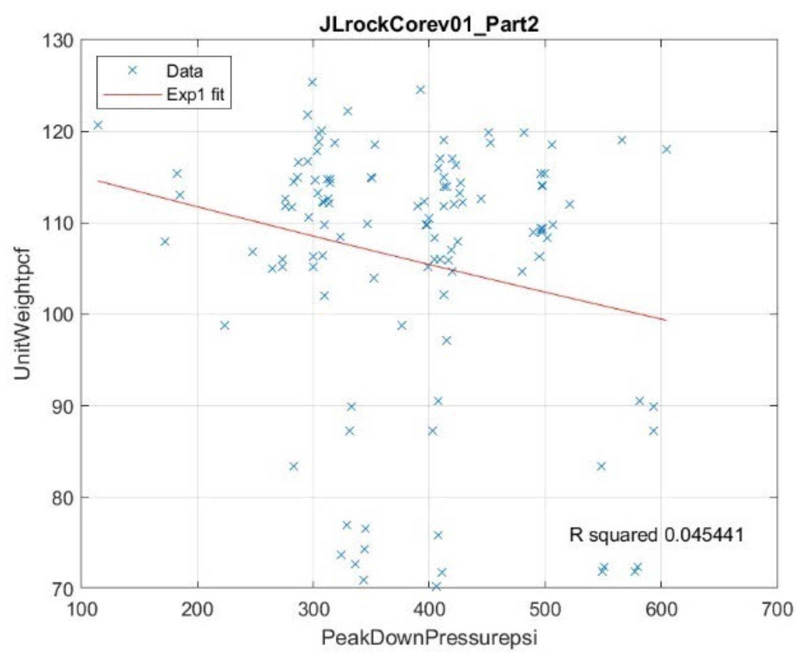


(f)

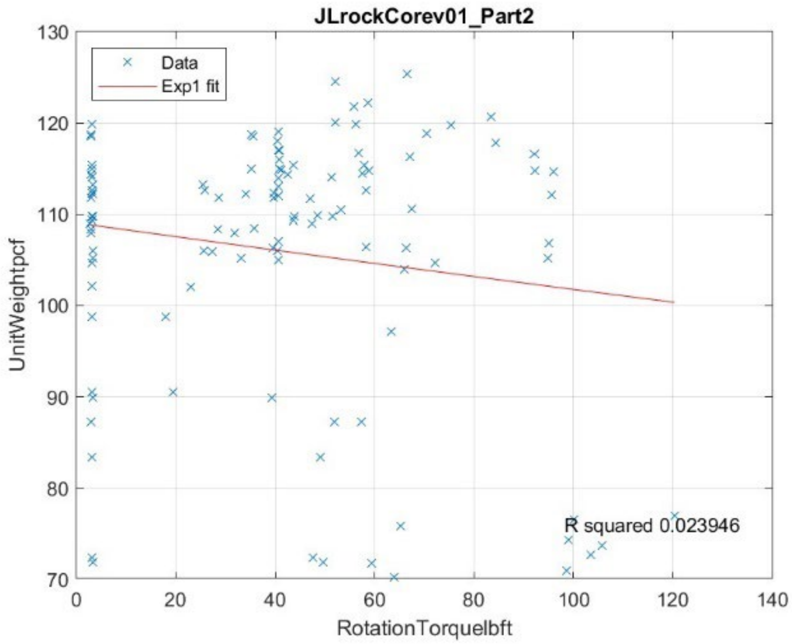
Figure 12. Single parameter linear regression correlation results for unit weight versus (a) depth, (b) down pressure, (c) torque, (d) rotation speed (e) moving speed and(f) specific energy. R^2 values are tabulated in Table 11.


JLrockCorev01_Part2
Data
Exp1 fit
R squared 0.18741
UnitWeightpcf
Depthfeet
130
120
110
100
90
80
70
20
25
30
35
40
45
50
55
60
65
70

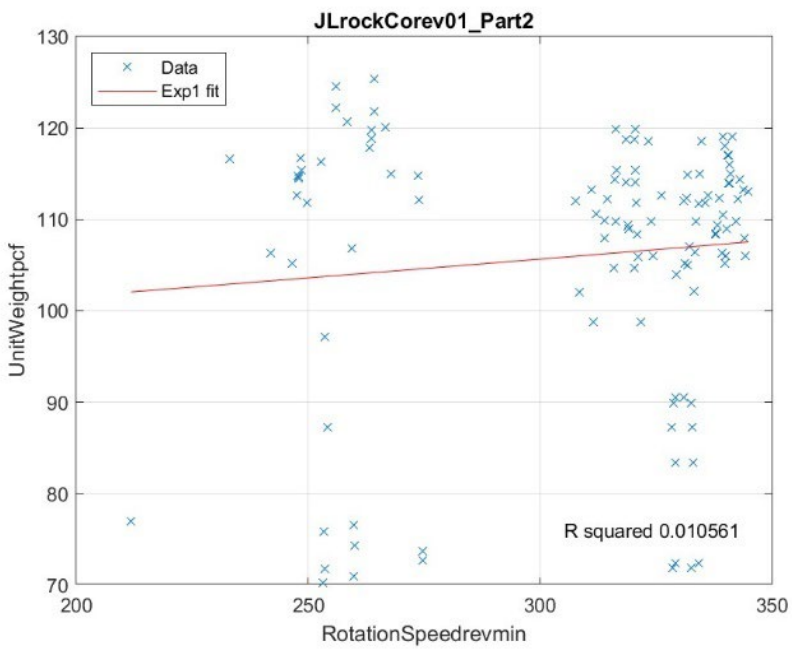
(a)


JLrockCorev01_Part2
Data
Exp1 fit
R squared 0.045441
UnitWeightpcf
PeakDownPressurepsi
130
120
110
100
90
80
70
100
200
300
400
500
600
700

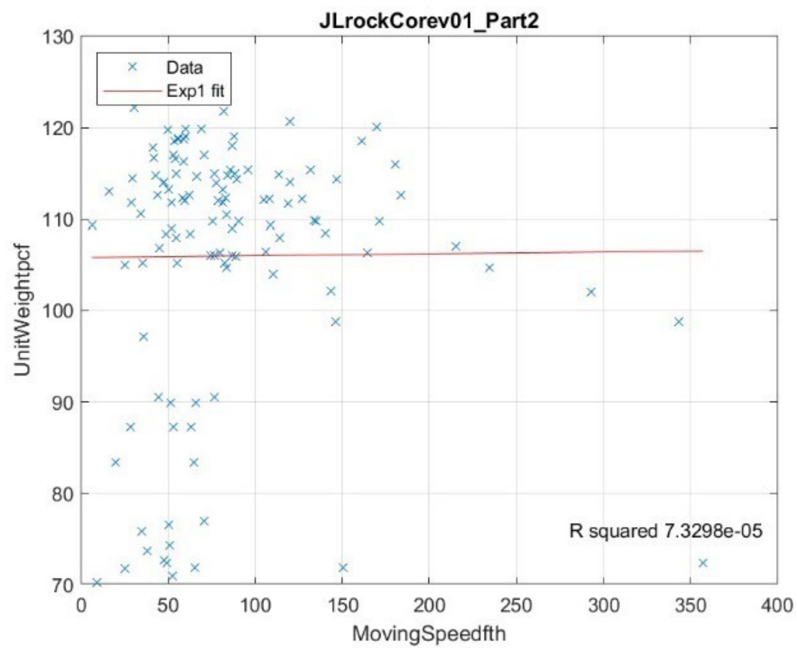
(b)


JLrockCorev01_Part2
Data
Exp1 fit
UnitWeightpcf
RotationTorquelbft
R squared 0.023946
130
120
110
100
90
80
70
0
20
40
60
80
100
120
140

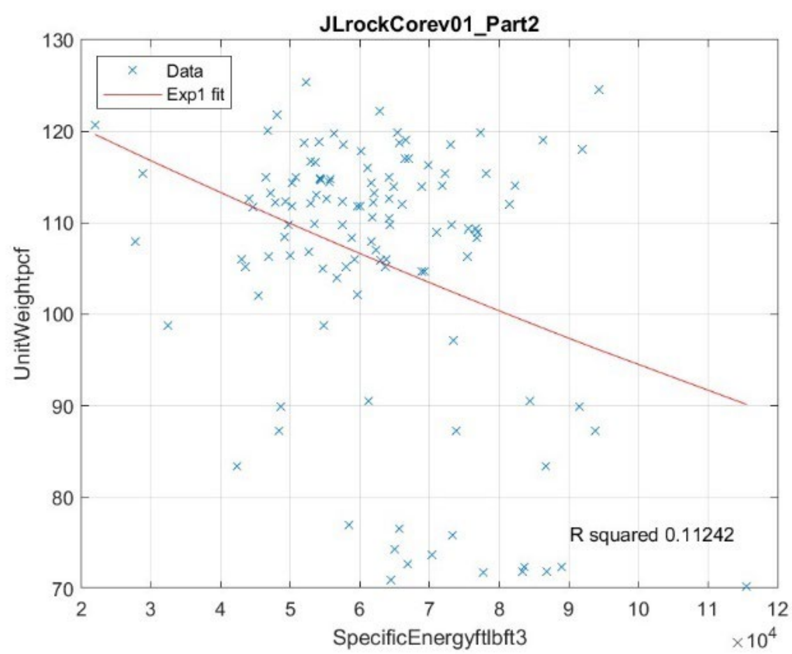
(c)


JLrockCorev01_Part2
Data
Exp1 fit
UnitWeightpcf
RotationSpeedrevmin
R squared 0.010561
130
120
110
100
90
80
70
200
250
300
350

(d)



(e)



(f)

Figure 13. Single parameter exponential regression correlation results for unit weight versus (a) depth, (b) down pressure, (c) torque, (d) rotation speed (e) moving speed and(f) specific energy.. MWD parameter used is shown on horizontal axis. R^2 values are tabulated in Table 11.

Table 11. Tabulated R^2 values for single parameter linear and exponential fitting for unit weight.

MWD parameter	Linear R^2	Exponential R^2
Depth	0.19	0.19
Down pressure	0.05	0.05
Rotation torque	0.02	0.02
Rotation speed	0.01	0.01
Moving speed	0.00	0.00
Specific energy	0.17	0.11

8.2. Phase 2: Multiple Parameter Linear Regression Modeling

Analysis of correlations using single parameter MWD parameters against SPT blow count, UCS and unit weight yielded correlations with poor predictive power as can be seen by the low Pearson correlation coefficient (R^2) values. Trying to understand the poor results, we speculated that working in IGM's categorized as extremely weak rock (35 to 150 psi) and very weak rock (150 to 725 psi) could be a major contributing factor. Another possibility was the fact that MWD data were collected in the same borehole that sampling was done which could have a possible impact on modifying the materials in situ.

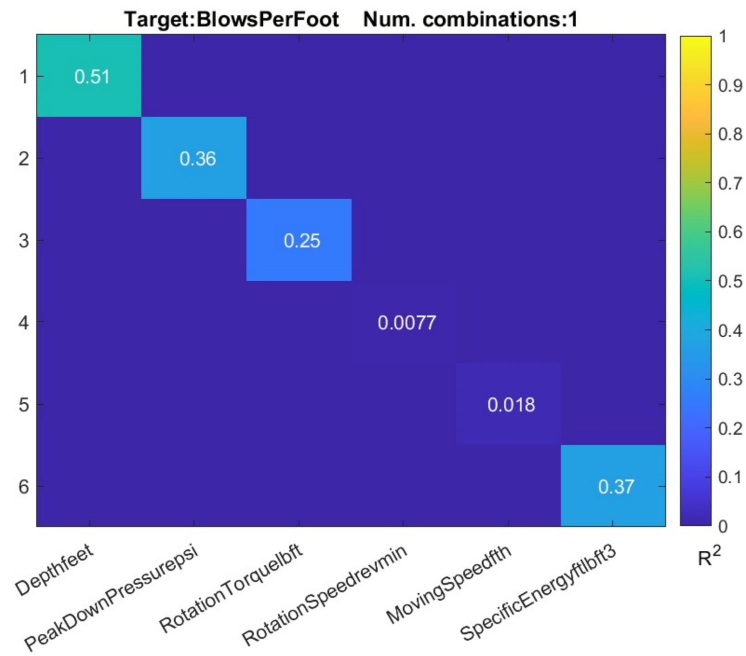
To further investigate *linear* correlation of MWD data and rock strength data, we implemented a multiple linear regression (MLR) approach. We used the same set of six MWD parameters as inputs and investigated correlations of these inputs to SPT blow count, UCS and unit weight – an approach similar to single parameter linear regression analysis. However, we explored all of the possible combinations of inputs in the analysis. That is, all possible combinations of six inputs using one input, all possible combinations of six inputs using two inputs, etc., up to the combination using all six inputs which resulted in 63 different combinations to test: 6 combinations using 1 input, 15 combinations using 2 inputs, 20 combinations using 3 inputs, 15 combinations using 4 inputs, 6 combinations using 5 inputs and 1 combination using all 6 inputs).

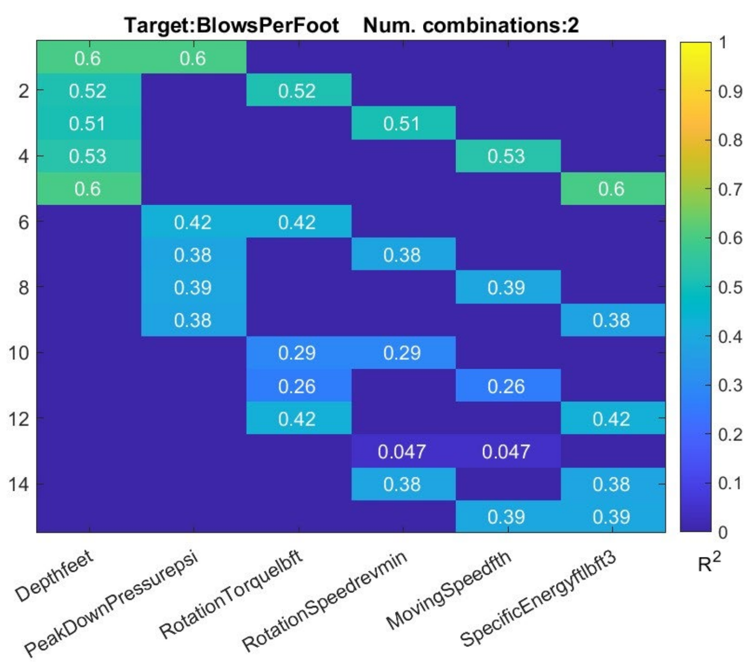
To display our results, we developed a graphical matrix approach. The matrix columns represent each of the possible six MWD inputs. The rows represent the number of possible combinations. The R^2 correlation coefficient for each correlation is displayed in each cell of the horizontal row for a particular combination. In addition to displaying the numerical R^2 value, the cells are color-coded on a scale of 0 to 1 with blue representing low R^2 values and yellow representing high R^2 values. Color-coding makes quick comparisons of various combinations easy for either a specific number of combinations or across various numbers of correlations.

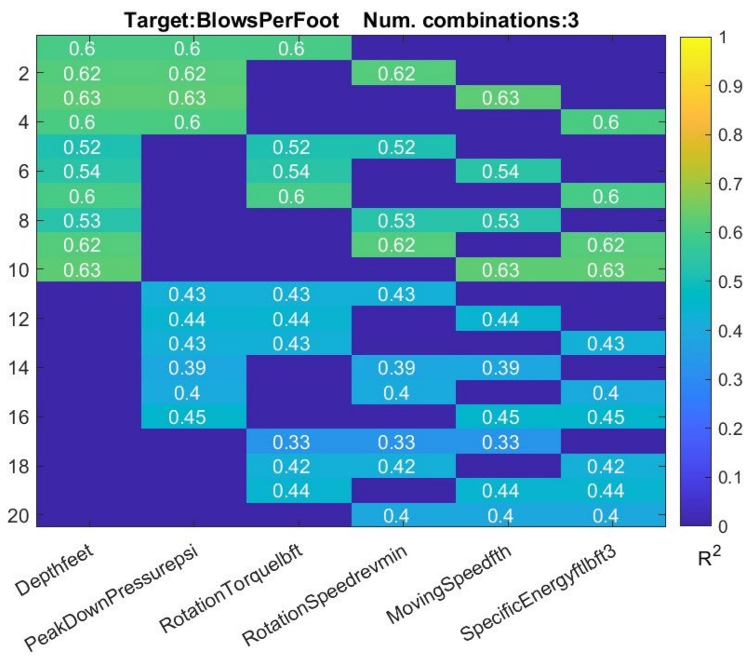
8.2.1. SPT Blow Count MLR Correlations

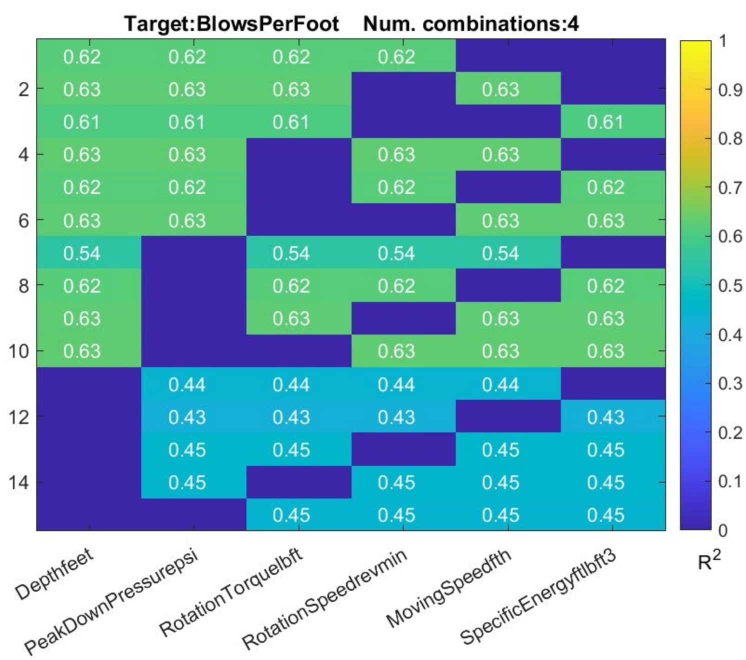
Figure 14 shows six matrix plots representing MLR correlation results for SPT blow counts. The first plot shows R^2 values for one combination of MWD inputs, the second plot shows R^2 results for all possible combinations of two inputs, and so on to the sixth plot which shows only one possible combination of the six MWD inputs.

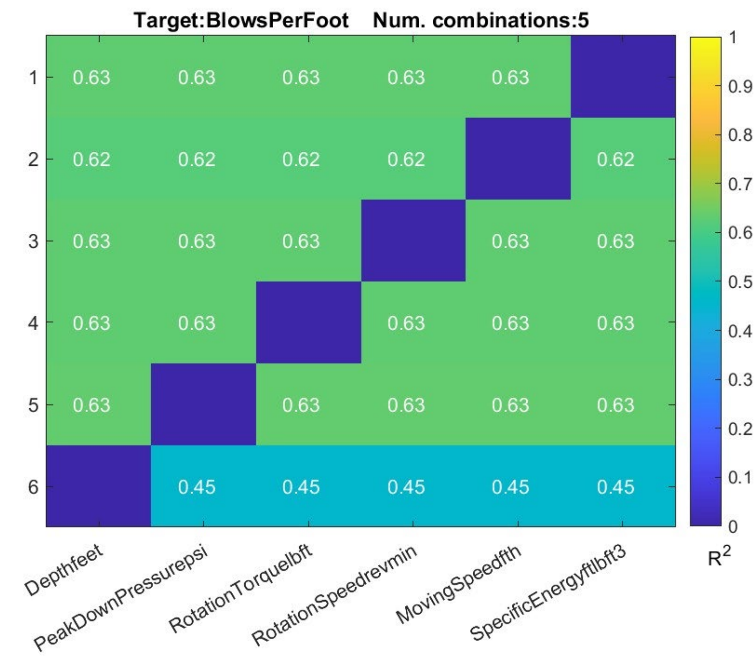
A text summary of MLR results for SPT blow count prediction is also shown in Appendix A.






Target:BlowsPerFoot Num. combinations:3
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R2


Target:BlowsPerFoot Num. combinations:4
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R2



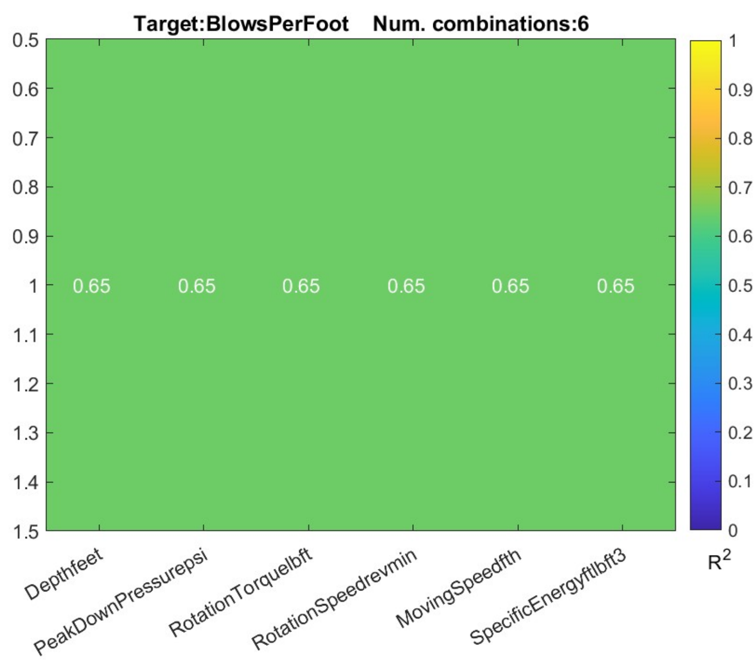
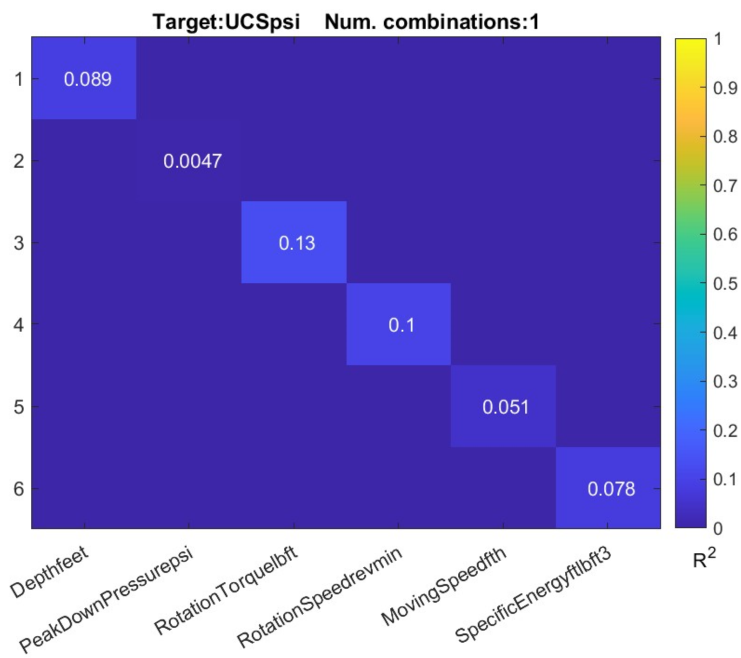


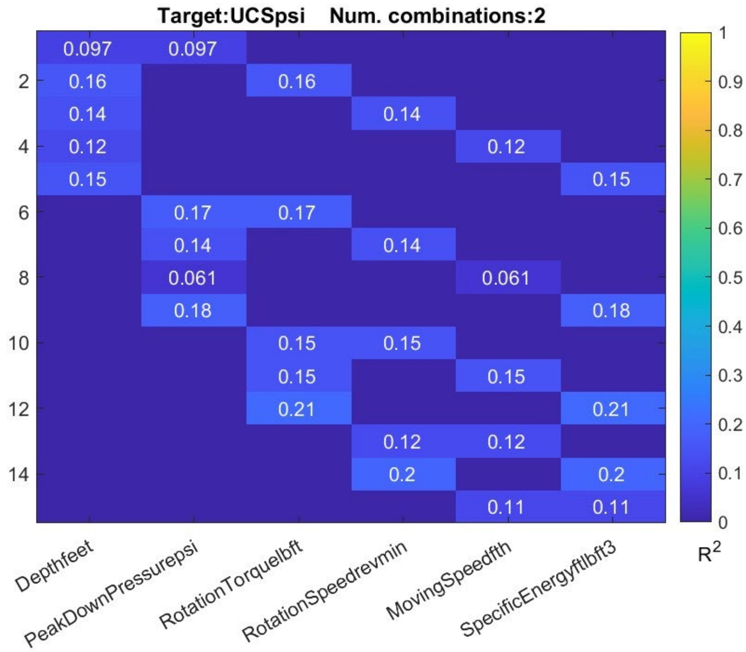
Figure 14. Six matrix plots showing MLR results for the target SPT blow counts. Matrix columns represent the six MWD inputs. Rows show MLR R^2 values in cells representing which of the six MWD inputs were used for the correlation. R^2 values are color-coded from blue to yellow for easy comparison in a single plot or across plots.

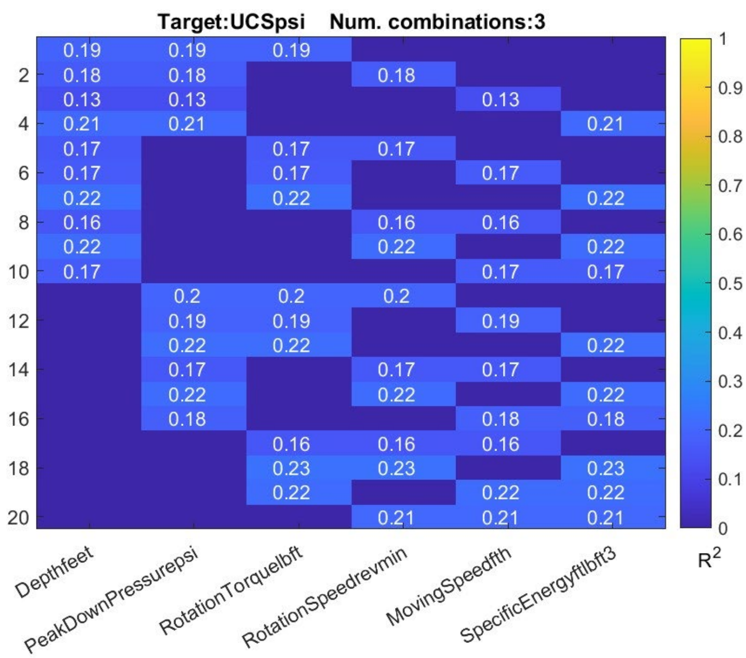
8.2.2. UCS MLR Correlations

Figure 15 shows the six matrix plots representing MLR correlation results for predicting UCS. Similar to SPT blow count results, the first plot shows R^2 values for one combination of MWD inputs, the second plot shows R^2 results for all possible combinations of two inputs, and so on to the sixth plot which shows only one possible combination of the six MWD inputs.

A text summary of MLR results for UCS prediction is shown in Appendix B.




Target:UCSpsi Num. combinations:2
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R^2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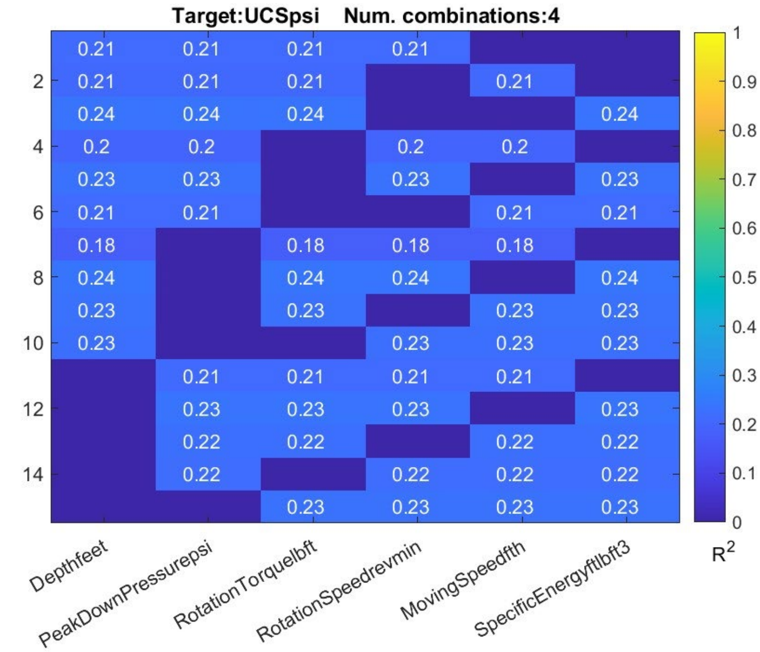
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R^2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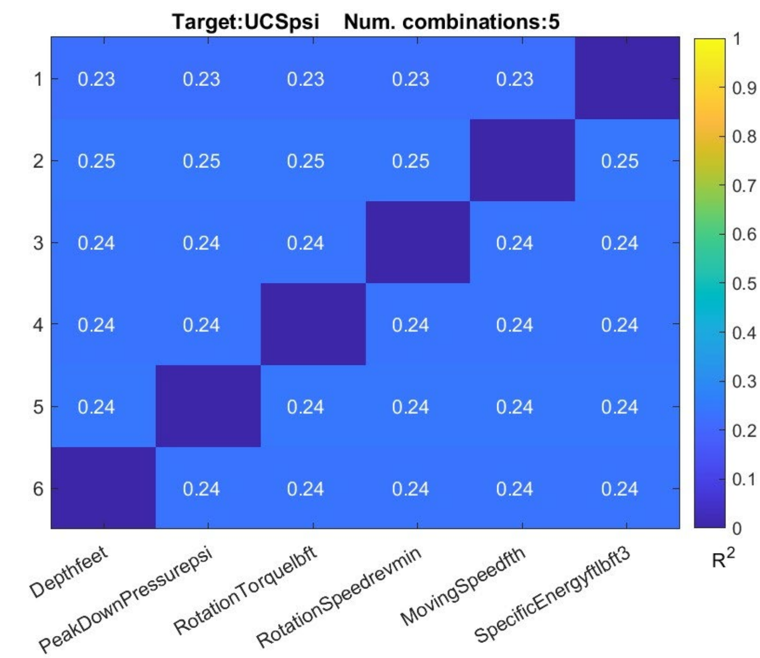
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R^2


Target:UCSpsi Num. combinations:5
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R^2

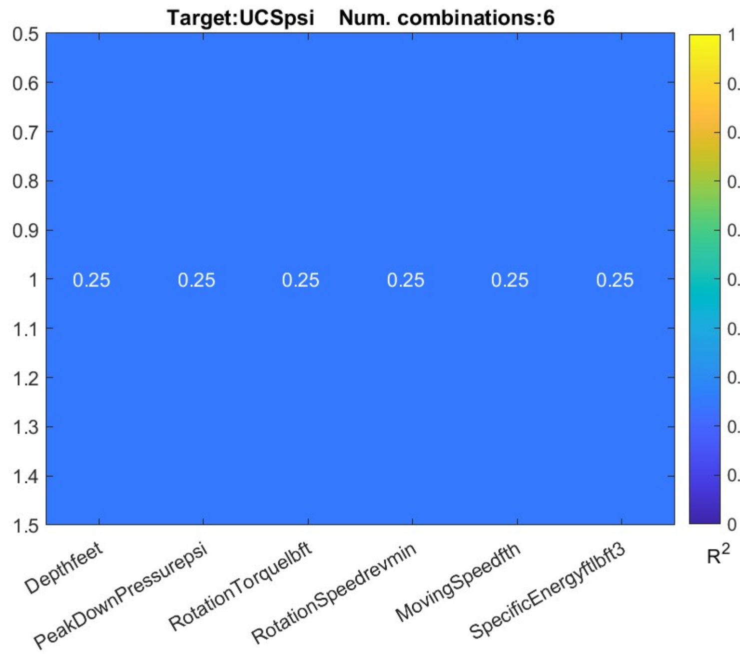
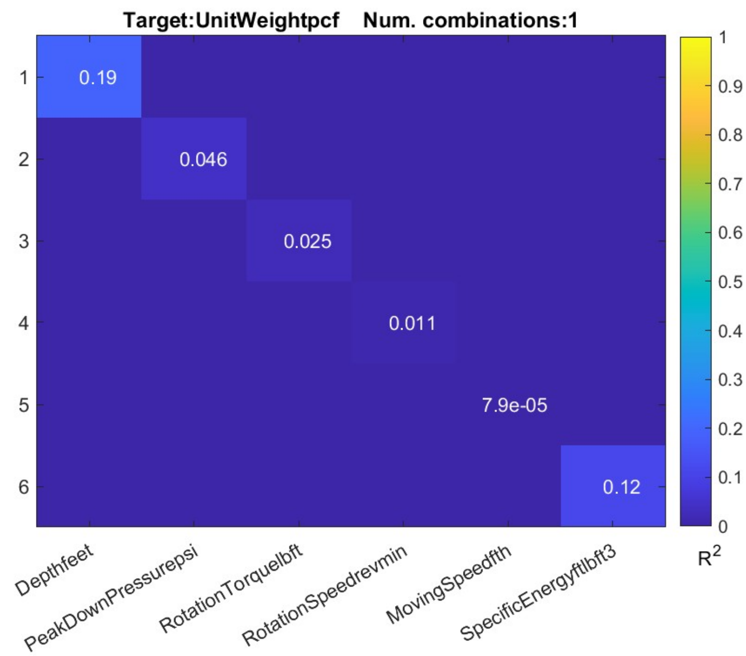


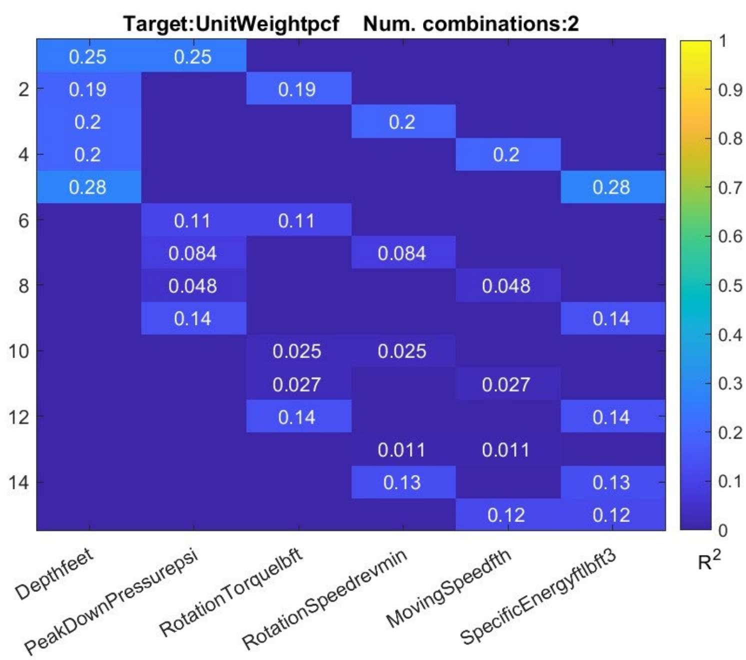
Figure 15. Six matrix plots showing MLR results for the target UCS. Matrix columns represent the six MWD inputs. Rows show MLR R^2 values in cells representing which of the six MWD inputs were used for the correlation. R^2 values are color-coded from blue to yellow for easy comparison in a single plot or across plots.

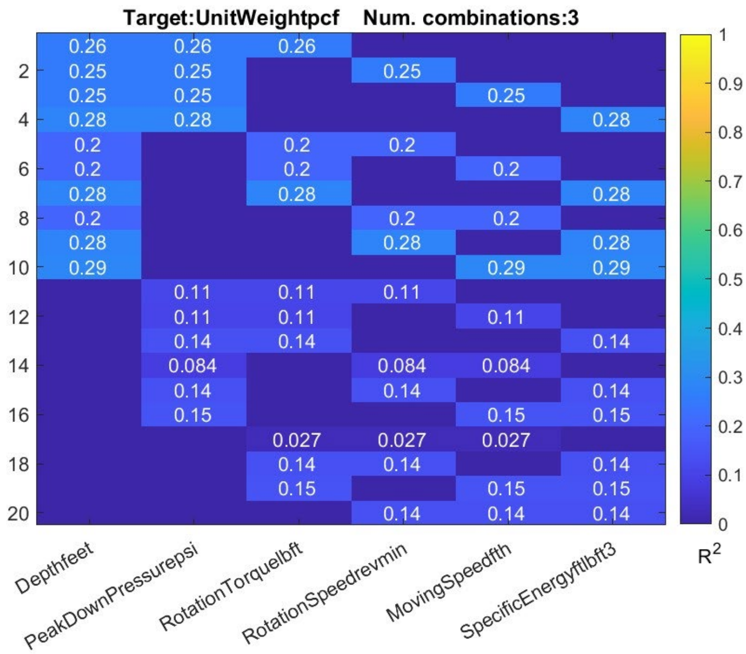
8.2.3. Unit Weight MLR Correlations

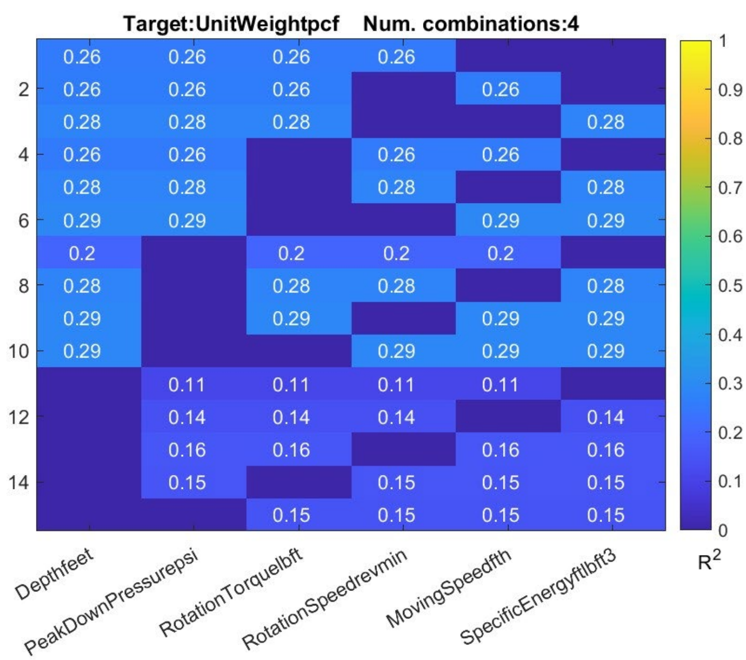
Figure 16 shows the six matrix plots representing MLR correlation results for predicting unit weight. The first plot shows R^2 values for one combination of MWD inputs, the second plot shows R^2 results for all possible combinations of two inputs, and so on to the sixth plot which shows only one possible combination of the six MWD inputs.

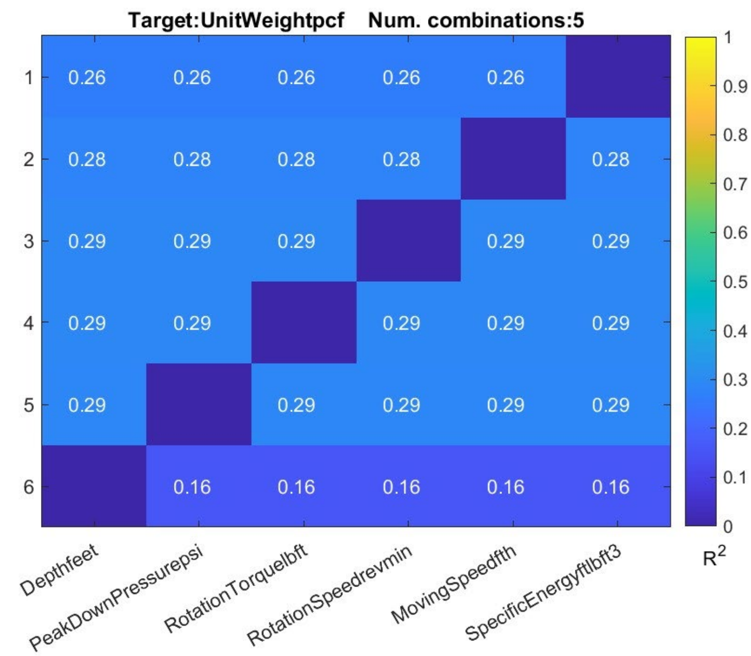
A text summary of MLR results for unit weight prediction is shown in Appendix C.


Target:UnitWeightpcf Num. combinations:1
0.19
0.046
0.025
0.011
7.9e-05
0.12
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R^2


Target:UnitWeightpcf Num. combinations:2
0.25 0.25
0.19 0.19
0.2 0.2
0.2 0.2
0.28 0.28
0.11 0.11
0.084 0.084
0.048 0.048
0.14 0.14
0.025 0.025
0.027 0.027
0.14 0.14
0.011 0.011
0.13 0.13
0.12 0.12
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R^2


Target:UnitWeightpcf Num. combinations:3
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R^2


Target:UnitWeightpcf Num. combinations:4
Depthfeet
PeakDownPressurepsi
RotationTorquelbft
RotationSpeedrevmin
MovingSpeedfth
SpecificEnergyftlbft3
R^2



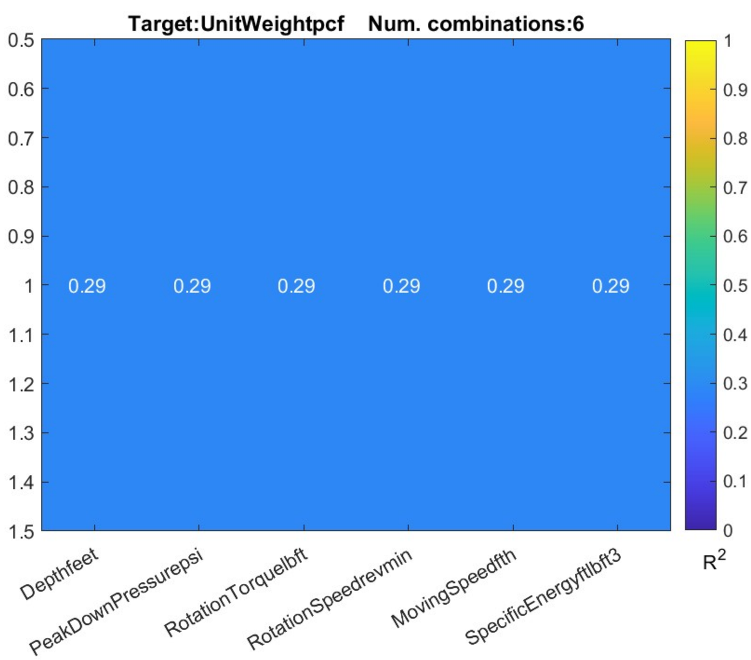


Figure 16. Six matrix plots showing MLR results for the target unit weight. Matrix columns represent the six MWD inputs. Rows show MLR R^2 values in cells representing which of the six MWD inputs were used for the correlation. R^2 values are color-coded from blue to yellow for easy comparison in a single plot or across plots.

8.3. Phase 3: Multiple Parameter Non-Linear Regression Modeling

Considering the overall weak predictive power of linear regression modeling as evidenced in the preceding sections, we next implemented a non-linear, neural network (NN) modeling approach. Literature is rich with many references for details of NN modeling. An especially useful reference is Hagan et al. (2014). Neural network modeling was implemented using Matlab® software and toolboxes (https://www.mathworks.com/). The Matlab® scripting environment allowed easy implementation of loops over the number of neurons used in the hidden layer and the number of trials to use for each hidden layer architecture. For our work, we modeled the hidden layer with [2 3 5 7 9 10 11 15 20 25 30] neurons and 100 trials for each hidden layer neuron number. In addition to varying the number of neurons in the hidden layer we used the same set of 63 possible combinations of inputs for each hidden layer setting. This resulted in 693 different NN model architectures to test with 100 iterations for each architecture.

Neural network modeling is a stochastic method. Each individual model is initiated with random initial weights and biases comprising the network (these are adjusted in training to decrease error in an iterative process). In addition, the input data set is divided into training (70%), validation (15%) and testing subsets (15%) which are randomly chosen for each trial. The network is trained using data from the training subset. The validation subset is used to dynamically monitor if error increases instead of decreasing and the independent testing subset is applied after training to test the generalization capability of the trained network. Figure 17 is a schematic illustrating the fitting network architecture we used showing inputs, hidden layer and output layer. Our modeling varied the number of inputs and the number of hidden layer neurons.

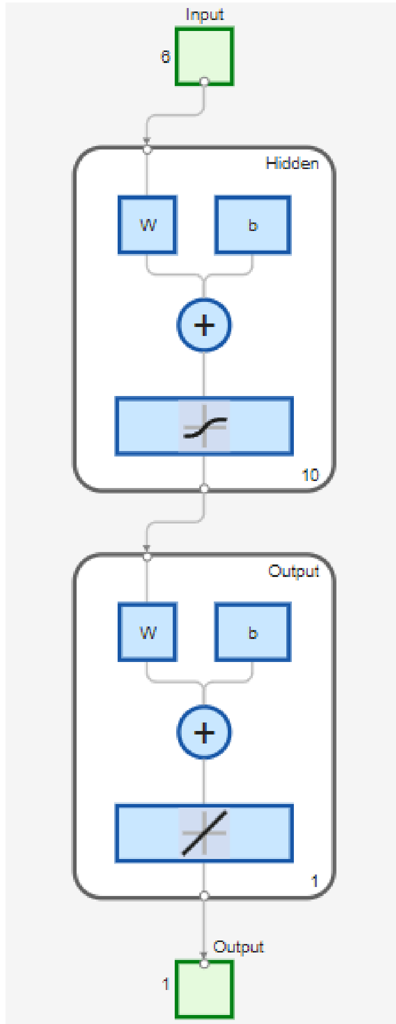


Figure 17. Feedforward fitting neural network schematic used for our analysis. Schematic shows 6 inputs (our inputs vary from 1 to 6), one hidden layer using a *tansig* transfer function with 10 neurons (our number of neurons varies from 2 to 30) with weights *w* and biases *b* and 1 output neuron with a *purelin* transfer function and one weight and bias. The output neuron produces a value for either SPT blow count, UCS or unit weight depending on which target set was used.

NN modeling used the same sets of input and target data used for linear correlation analysis: SPT blow count data (n = 64) and UCS and unit weight data (n = 117). To show NN modeling results, we generated plots of model predictions vs. targets and calculated the coefficient of determination R^2 to quantify goodness of fit. R^2 values are calculated for the training, validation and testing subsets as well as for the entire data set (all). Two sets of plots were produced: plots showing the *mean* R^2 values for 100 trials for each hidden layer number of neurons and a plot showing the *best* R^2 value out of the 100 trials for each hidden layer number of neurons.

The NN modelling results are presented in Appendices D, E and F. Each appendix contains two sets of results (D-1, D-2, E-1, E-2, F-1, F-2). The first appendix subset (e.g. D-1) shows plots for the approximately six best models displaying mean R^2 values and best R^2 values for the 100 trials for each NN architecture (i.e. number of neurons in the hidden layer). The particular inputs that resulted in the best models are shown on the plots by number: 1 – Depthfeet, 2 – PeakDownPressurepsi, 3 - RotationTorquelbft, 4 – RotationSpeedrevmin, 5 – MovingSpeedfth, 6 - SpecificEnergyftlbft3.

The best model results shown came from 63 scenarios. The number of scenarios results from the total possible number of input combinations: 6 combinations using 1 input, 15 combinations using 2 inputs, 20 combinations using 3 inputs, 15 combinations using 4 inputs, 6 combinations using 5 inputs and 1 combination using all 6 inputs. On each plot, the horizontal axis shows the number of neurons used in the hidden layer for each scenario. Mean R^2 and best R^2 are displayed using four colors: blue for training, green for validation, red for testing and black for all. These plots are useful for quick comparisons of performance of the various NN scenarios.

In addition to the plots, a second appendix subset (e.g. D-2) contains a text listing of mean R^2 and best R^2 values for each of the best models plotted in the first appendix subset.

The complete text list for all models along with plots has been archived. Furthermore, each of the NN model architectures for best R^2 results is also saved to the same folder. This allows the user, after NN training, to review the performance results and choose the saved NN that has the best R^2 performance for a specified number of neurons in the hidden layer from the best combination of the six inputs. This represents the application phase of NN modelling. At this point, the user chooses the desired trained NN model and presents new MWD data resulting in a prediction of either SPT blow counts, UCS or unit weight. The application phase is analogous to having a regression equation and providing a new independent variable to produce the new dependent variable (i.e., present a new ‘x’ to the regression equation to get a new ‘y’).

8.3.1. NN SPT Blow Count Prediction

Prior to beginning NN modelling, we used an F-test to compare the importance of the contribution of each of the six input variables to predicting the desired target. We implemented the F-test using the built-in F-test function in Matlab®.

Figure 18 is a bar plot showing the relative importance of each of the six inputs to predicting SPT blow counts. The F-test calculations are based on comparison of variances of two parameters.

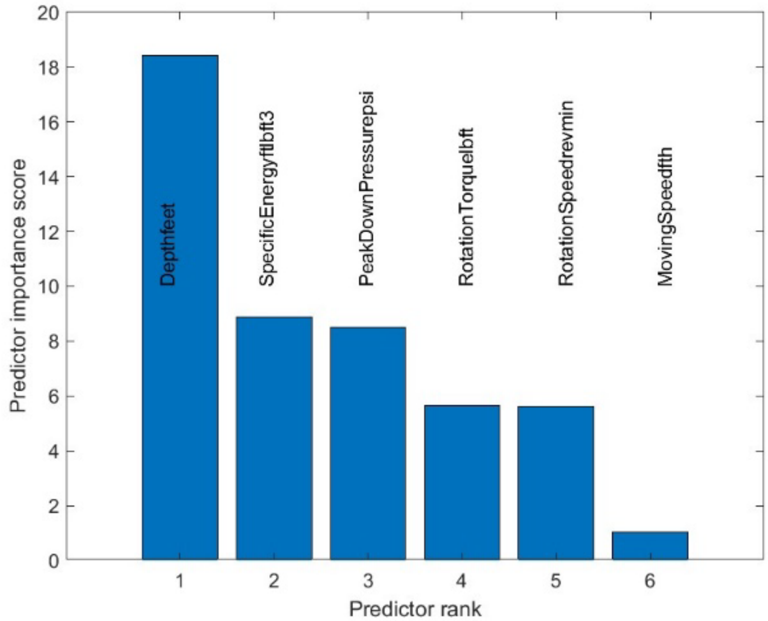


Figure 18. Bar plot showing the relative importance of the six input parameters in predicting unit weight. Each column is labeled with the name of the corresponding input parameter. For unit weight modelling, depth has the greatest relative importance in predicting unit weight; moving speed the least.

Results for NN modelling of SPT blow counts are presented in Appendices D-1 and D-2 as described in section 8.3. Appendix D-1 contains two sets of 6 network model plots (mean R^2 and best R^2 for 100 trials). Appendix D-2 contains the text list of the 6 best NN models.

8.3.2. NN UCS Prediction

Prior to NN modelling for UCS, we used the F-test to compare the importance of the contribution of each of the six input variables to predicting UCS. The F-test was implemented using the built-in F-test function in Matlab®.

Figure 19 is a bar plot showing the relative importance of each of the six inputs to predicting UCS. The F-test calculations are based on comparison of variances of two parameters.

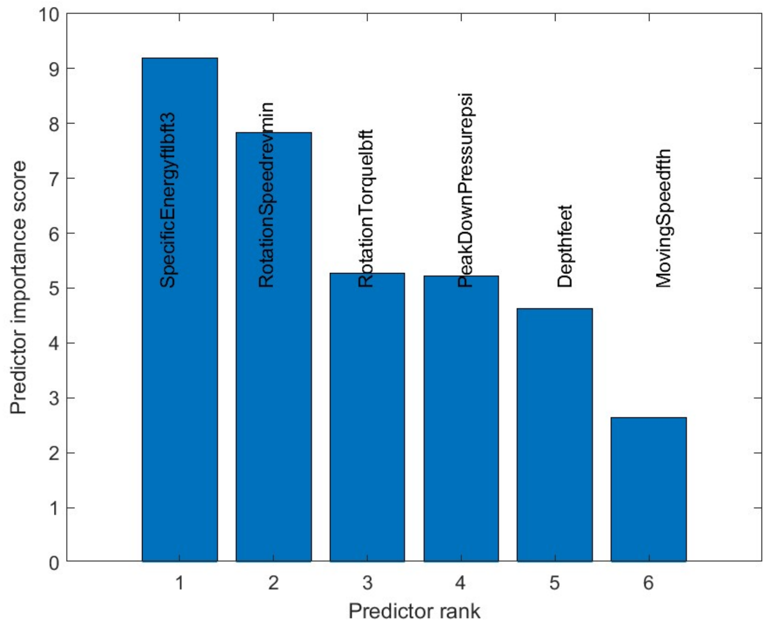


Figure 19. Bar plot showing the relative importance of the six input parameters in predicting UCS. Each column is labeled with the name of the corresponding input parameter. For UCS modelling, specific energy has the greatest relative importance in predicting UCS; moving speed the least.

Results for NN modelling of UCS are presented in Appendices E-1 and E-2 as described in section 8.3. Appendix E-1 contains the two sets of 63 network scenario plots (mean R^2 and best R^2 for 100 trials). Appendix E-2 contains a subset of the full text list of the 693 NN scenarios.

8.3.3. NN Unit Weight Prediction

Prior to NN modelling for unit weight, we used the F-test to compare the importance of the contribution of each of the six input variables to predicting unit weight. The F-test was implemented using the built-in F-test function in Matlab®.

Figure 20 is a bar plot showing the relative importance of each of the six inputs to predicting unit weight.

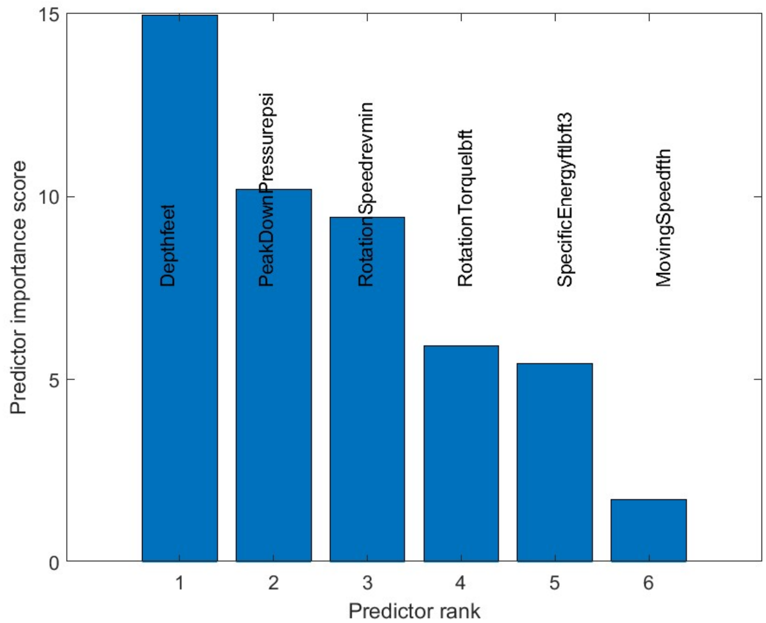


Figure 20. Bar plot showing the relative importance of the six input parameters in predicting unit weight. Each column is labeled with the name of the corresponding input parameter. For unit weight modelling, depth has the greatest relative importance in predicting unit weight; moving speed the least.

9. Discussion

9.1. Data Subsets

As stated in the proposal and contract, the focus of Task 2 was investigation of correlations between MWD measurements and geotechnical parameters of interest. After assembling and organizing MWD data and geotechnical data, initial investigation explored linear correlations. It quickly became apparent that the streams of recorded MWD data required significant user input for data quality control. Specifically, for developing correlations of MWD and SPT blow count data, it was necessary to extract a small subset of values from the recorded data stream. As detailed in section 5, the down pressure data stream recorded sharp drops in measured pressure when auger changes happened. Our approach was to identify the pressure values before the sharp drops and use those pressures and corresponding MWD measurements for SPT blow count correlations.

Similarly, for UCS and unit weight correlations, we identified the MWD values associated with the UCS and unit weight lab values at those depths and used that data subset for correlation analysis. In addition, we evaluated the lab measurement values for unrealistic values.

After inspection of MWD data, we ended up with a data set for SPT blow count correlations of 64 examples. For UCS and unit weight correlations, we used 117 data examples. These data sets are described in sections 6.2 and 6.3 of this report.

For correlation analysis we used six inputs from MWD measurements: depth, down pressure, rotation torque, rotation speed, moving speed and the compound parameter specific energy.

9.2. Single Parameter Linear Correlations – Phase 1

Correlation results for single parameter linear correlation are detailed in section 8.1 in this report. We used the coefficient of determination (R^2) to quantify goodness of fit. The single best R^2 value was 0.49 for depth and SPT blow counts. Tables in section 8.1 summarize the results. Figures in section 8.1 show plots with the linear regression fit lines overlain on the data used. Correlation results for UCS and unit weight were very low. Obviously, this approach was not going to be of use for any prediction analysis.

9.3. Evaluating The Relative Importance of Inputs

An F-test was used to evaluate the relative importance of the six individual inputs to predict each of the three targets: SPT blow counts, UCS and unit weight. The results of the F-tests are presented at the beginning of sections 8.3.1, 8.3.2 and 8.3.3. Interestingly, depth is an important predictive variable for both SPT blow count and unit weight predictions.

Although the F-test provides a useful tool for evaluating the relative importance of inputs in modelling, a more comprehensive insight is obtained by reviewing results from both MLR (multiple linear regression) and NN modelling. For MLR, results are shown as matrix values in graphical form and as text listings in Appendices A, B and C. Each row in the plots or text listing represents a single combination of inputs. The highlighted cells on the plots are populated with the MLR correlation coefficient for those particular inputs. These values can be viewed as giving the importance of that combination of inputs.

For NN modelling, we can look at either the plots of modelling results, or the text listings. These are shown in Appendices D, E and F. The text listing shows the four correlation coefficients (training, validation, testing and all) for each of the 63 combinations as well as varying that over the number of neurons in the hidden layer resulting in 693separate sets of results.

9.4. Multiple Parameter Linear Correlations – Phase 2

Considering the poor correlation results for single parameter linear correlation, we implemented a multiple parameter linear approach. Details are discussed in section 8.2 of this report. Continuing with the six MWD inputs, we calculated all of the possible combinations of those inputs resulting in 63 possible sets of inputs. We calculated the multiple linear regressions (MLR) for those input sets for the same geotechnical parameters: SPT blow counts, UCS and unit weight. MLR results are detailed in section 8.2 and shown in Appendices A, B and C.

The appendices show the results in text form; figures in section 8.2 show the result in graphic form. As the number of inputs increased, MLR R^2 values also increased. The highest R^2 value of

0.65 occurred for correlating SPT blow counts with all six possible inputs. Best correlation values for UCS and unit weight also occurred with all six inputs but were still low at 0.25 for UCS and 0.29 for unit weight.

MLR results showed a significant improvement over single parameter linear results, likely indicating that we are dealing with a multiparameter process; not surprizing considering complicated geologic conditions.

9.5. Multiple Parameter Nonlinear Correlations – Phase 3

In light of the correlation improvements with MLR, we next implemented a nonlinear, multiple parameter approach in the context of machine learning (ML). There are a variety of ML techniques to explore including classification and clustering. Methods can be broadly grouped as supervised or unsupervised. Unsupervised approaches explore data sets to identify groupings without user intervention. Supervised approaches require known *targets* to train to. Both techniques are iterative methods and begin with a starting model guess or estimation or randomized model parameters.

We chose to use a supervised neural network (NN) approach because we are correlating inputs with known geotechnical parameters (targets). Also, in the framework of exploring models, we can implement multiple models in a programming environment that does not require user intervention for individual models. We used Matlab®'s Statistics and Machine Learning Toolbox to implement the modelling.

We used the same sets of 63 possible combinations of inputs we used for MLR in NN modelling. Additional variables in NN modelling are the number of hidden layers and the number of neurons in each hidden layer. We used a single hidden layer with number of neurons varying from 2 3 5 7 9 10 11 15 20 25 30 (11 possibilities). This results in 693 modeling scenarios. For each of these scenarios, we used 100 trials. For each trial, we recorded the best trial based on regression results as well as the mean regression results. Section 8.3 details results for predictions of SPT blow counts, UCS and unit weight. Results are presented in Appendices D, E and F as plots and in Appendices G, H and I in text format.

Results for nonlinear NN modeling showed large improvements in predictive ability. Compared to best case R^2 values of 0.65. 0.25 and 0.29 for MLR, we see a best R^2 of 0.91 for SPT blow counts, a best R^2 of 0.75 for UCS and a best R^2 of 0.86 for unit weight.

9.6. Final Models

9.6.1. Phase 1 Final Models – Single Parameter Linear/Exponential Regression

The best result for traditional, linear correlation for SPT blow counts is 0.51 R^2 resulting from using the input of measured depth.

The best result for traditional correlation for UCS is 0.18 R^2 using an exponential fit and input of rotational torque.

The best result for traditional correlation for unit weight is 0.19 R^2 using either a linear or exponential fit and the input of measured depth.

9.6.2. Phase 2 Final Models – Multiple Parameter Linear Regression

The best result for multiple linear regression for SPT blow counts is 0.65 R^2 using all six MWD inputs.

The best result for multiple linear regression for UCS is 0.25 R^2 using all six MWD inputs or the combination of depth, down pressure, rotation torque, rotation speed and specific energy.

The best result for multiple linear regression for unit weight is 0.29 R^2 using all six MWD inputs, or depth, moving speed, specific energy, or depth, down pressure, moving speed, specific energy, or depth, rotation torque, moving speed, specific energy, or depth, rotation speed, moving speed, specific energy, or almost any of the combinations of five inputs which use depth.

9.6.3. Phase 3 Final Models – Nonlinear Fitting Using Neural Networks

SPT Results

The best result for neural network fitting for SPT blow counts was a model using five inputs: depth, peak down pressure, rotation torque, rotation speed and moving speed. The sum of R^2 values for training, validation, testing and all was 3.64/4.0 using 15 neurons in the hidden layer. Table 12 shows results for additional models with high sum R^2 values.

Table 12. List of models with high sum R^2 values for SPT NN modelling.

Depth	Down pressure	Rotation torque	Rotation speed	Moving speed	Specific energy	HL no.	Sum R^2
✓	✓		✓	✓		9	3.54
✓			✓	✓	✓	15	3.61
✓	✓	✓	✓	✓		10	3.51
✓	✓	✓	✓	✓		15	3.64
✓	✓	✓	✓		✓	9	3.53
✓	✓		✓	✓	✓	11	3.52

UCS Results

The best result for neural network fitting for UCS was a model using four inputs: down pressure, rotation torque, moving speed and specific energy. The sum of R^2 values for training, validation, testing and all was 2.99/4.0 using 30 neurons in the hidden layer. Table 13 shows results for additional models with high sum R^2 values.

Table 13. List of models with high sum R^2 values for UCS NN modelling.

Depth	Down pressure	Rotation torque	Rotation speed	Moving speed	Specific energy	HL no.	Sum R^2
✓				✓		10	2.77
			✓		✓	20	2.86
	✓	✓		✓	✓	30	2.99
	✓		✓	✓	✓	25	2.83

Unit Weight Results

The best result for neural network fitting for unit weight was a model using three inputs: depth, down pressure and rotation torque. The sum of R^2 values for training, validation, testing and all was 3.43/4.0 using 25 neurons in the hidden layer. Table 14 shows results for additional models with high sum R^2 values.

Table 14. List of models with high sum R^2 values for UW NN modelling.

Depth	Down pressure	Rotation torque	Rotation speed	Moving speed	Specific energy	HL no.	Sum R^2
✓	✓	✓				25	3.43
✓		✓			✓	25	3.32
✓	✓	✓		✓		5	3.35
✓	✓	✓		✓		7	3.31
✓		✓	✓		✓	20	3.35
	✓	✓	✓		✓	9	3.35
✓	✓	✓	✓		✓	9	3.32

9.7. Looking Ahead

MWD is a relatively new approach for answering relevant questions about subsurface parameters. MWD technology and standards are evolving as we speak. Developing robust recording technology on the drill rig is not a trivial challenge. Revisiting drilling methodology and training MWD drillers will be critical to achieving high data quality. As the technology is applied in new geologic settings, new analysis techniques will need to be evaluated.

The takeaways from the current MDT project highlight drilling methodology for consistent, usable data and analysis techniques to explore nonlinear relationships among MWD parameters and geotechnical parameters.

Suggestions for future MWD projects are to consider a separate borehole for the sole purpose of collecting MWD data adjacent to a borehole used for HSA sampling and rock coring along with focused training for MWD drillers with input from other MWD practitioners. Such training would include how drilling methodology affects final MWD data quality and how these data are used for analysis. We think it is important to involve the driller in reviewing MWD and geotechnical data to inform best drilling practices for optimum data quality.

10. Conclusions and Recommendations

- Successful correlation of MWD data to geotechnical parameters requires careful preprocessing of MWD data and quality control/editing of drilling data such as UCS or SPT N. In addition, any correlations developed will be site specific and closely correlated with the local geology.
- The geology at MWD sites for the Montana project consisted of intermediate geomaterials (IGMs) categorized as extremely weak rock (35 to 150 psi) and very weak rock (150 to 725 psi). These weak materials present a challenge to the MWD drilling process and ultimately data analysis and correlation development.
- Future MWD work should focus on controlling the drilling environment to achieve optimized drilling parameters for highest drilling efficiency and optimal core recovery to achieve high quality MWD data. This approach may require dedicated MWD drillers adhering to standards developed by organizations involved. In addition, drilling a second adjacent borehole specifically for MWD data collections should be explored.
- Our work with MWD data from IGMs indicates that the relationship between MWD drilling parameters and correlations with geotechnical parameters is likely nonlinear.

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12. Acknowledgements

The majority of the bibliography is the effort of Mohammadhossein Sadeghiamirshahidi, Ph.D., A.M. ASCE. Mohammad had left Montana Tech after the initial proposal was written and his proposal was adapted and put into place for the research team at Montana Tech.

Appendices

Appendix A – MLR SPT Blows Per Foot

------- MLR ---------

---> Target = BlowsPerFoot

---- Number of combinations = 1
Depthfeet R squared = 0.50963
PeakDownPressurepsi R squared = 0.36366
RotationTorquelbft R squared = 0.25189
RotationSpeedrevmin R squared = 0.0077129
MovingSpeedfth R squared = 0.017877
SpecificEnergyftlbft3 R squared = 0.36605

---- Number of combinations = 2
Depthfeet PeakDownPressurepsi R squared = 0.60025
Depthfeet RotationTorquelbft R squared = 0.51796
Depthfeet RotationSpeedrevmin R squared = 0.51058
Depthfeet MovingSpeedfth R squared = 0.53243
Depthfeet SpecificEnergyftlbft3 R squared = 0.59937
PeakDownPressurepsi RotationTorquelbft R squared = 0.42455
PeakDownPressurepsi RotationSpeedrevmin R squared = 0.37985
PeakDownPressurepsi MovingSpeedfth R squared = 0.38953
PeakDownPressurepsi SpecificEnergyftlbft3 R squared = 0.37529
RotationTorquelbft RotationSpeedrevmin R squared = 0.28888
RotationTorquelbft MovingSpeedfth R squared = 0.26066
RotationTorquelbft SpecificEnergyftlbft3 R squared = 0.42397
RotationSpeedrevmin MovingSpeedfth R squared = 0.046513
RotationSpeedrevmin SpecificEnergyftlbft3 R squared = 0.38316
MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.39421

---- Number of combinations = 3
Depthfeet PeakDownPressurepsi RotationTorquelbft R squared = 0.60039
Depthfeet PeakDownPressurepsi RotationSpeedrevmin R squared = 0.6169
Depthfeet PeakDownPressurepsi MovingSpeedfth R squared = 0.62666
Depthfeet PeakDownPressurepsi SpecificEnergyftlbft3 R squared = 0.60485
Depthfeet RotationTorquelbft RotationSpeedrevmin R squared = 0.51798
Depthfeet RotationTorquelbft MovingSpeedfth R squared = 0.53789
Depthfeet RotationTorquelbft SpecificEnergyftlbft3 R squared = 0.59945
Depthfeet RotationSpeedrevmin MovingSpeedfth R squared = 0.53443
Depthfeet RotationSpeedrevmin SpecificEnergyftlbft3 R squared = 0.61634
Depthfeet MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.62705
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin R squared = 0.42501

PeakDownPressurepsi RotationTorquelbft MovingSpeedfth   R squared = 0.44232
PeakDownPressurepsi RotationTorquelbft SpecificEnergyftlbft3   R squared = 0.42569
PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth   R squared = 0.39281
PeakDownPressurepsi RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.39965
PeakDownPressurepsi MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.45037
RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.33081
RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.42464
RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.4434
RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.39758

---- Number of combinations = 4
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin   R squared = 0.62068
Depthfeet PeakDownPressurepsi RotationTorquelbft MovingSpeedfth   R squared = 0.62676
Depthfeet PeakDownPressurepsi RotationTorquelbft SpecificEnergyftlbft3   R squared = 0.60725
Depthfeet PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth   R squared = 0.63007
Depthfeet PeakDownPressurepsi RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.61831
Depthfeet PeakDownPressurepsi MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.62837
Depthfeet RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.54391
Depthfeet RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.62073
Depthfeet RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.62724
Depthfeet RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.63044
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.44467
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.42569
PeakDownPressurepsi RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.45449
PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.45203
RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.44547

---- Number of combinations = 5
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.63216
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.62074
Depthfeet PeakDownPressurepsi RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.63139
Depthfeet PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.63144
Depthfeet RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.63298
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.45449

---- Number of combinations = 6
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.64512

Appendix B – MLR UCS

------- MLR ---------

---> Target = UCSpsi

---- Number of combinations = 1
Depthfeet R squared = 0.088592
PeakDownPressurepsi R squared = 0.0046785
RotationTorquelbft R squared = 0.13225
RotationSpeedrevmin R squared = 0.10315
MovingSpeedfth R squared = 0.050543
SpecificEnergyftlbft3 R squared = 0.07835

---- Number of combinations = 2
Depthfeet PeakDownPressurepsi R squared = 0.096613
Depthfeet RotationTorquelbft R squared = 0.15775
Depthfeet RotationSpeedrevmin R squared = 0.14069
Depthfeet MovingSpeedfth R squared = 0.12097
Depthfeet SpecificEnergyftlbft3 R squared = 0.14908
PeakDownPressurepsi RotationTorquelbft R squared = 0.17245
PeakDownPressurepsi RotationSpeedrevmin R squared = 0.14307
PeakDownPressurepsi MovingSpeedfth R squared = 0.060659
PeakDownPressurepsi SpecificEnergyftlbft3 R squared = 0.1816
RotationTorquelbft RotationSpeedrevmin R squared = 0.14531
RotationTorquelbft MovingSpeedfth R squared = 0.14708
RotationTorquelbft SpecificEnergyftlbft3 R squared = 0.20815
RotationSpeedrevmin MovingSpeedfth R squared = 0.12432
RotationSpeedrevmin SpecificEnergyftlbft3 R squared = 0.19532
MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.1146

---- Number of combinations = 3
Depthfeet PeakDownPressurepsi RotationTorquelbft R squared = 0.19317
Depthfeet PeakDownPressurepsi RotationSpeedrevmin R squared = 0.17533
Depthfeet PeakDownPressurepsi MovingSpeedfth R squared = 0.13392
Depthfeet PeakDownPressurepsi SpecificEnergyftlbft3 R squared = 0.21037
Depthfeet RotationTorquelbft RotationSpeedrevmin R squared = 0.16644
Depthfeet RotationTorquelbft MovingSpeedfth R squared = 0.17115
Depthfeet RotationTorquelbft SpecificEnergyftlbft3 R squared = 0.22397
Depthfeet RotationSpeedrevmin MovingSpeedfth R squared = 0.1582
Depthfeet RotationSpeedrevmin SpecificEnergyftlbft3 R squared = 0.21717
Depthfeet MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.17261
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin R squared = 0.19811

PeakDownPressurepsi RotationTorquelbft MovingSpeedfth   R squared = 0.18953
PeakDownPressurepsi RotationTorquelbft SpecificEnergyftlbft3   R squared = 0.22136
PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth   R squared = 0.16713
PeakDownPressurepsi RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.21806
PeakDownPressurepsi MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.18346
RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.15767
RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.22874
RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.21562
RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.20536

---- Number of combinations = 4
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin   R squared = 0.21255
Depthfeet PeakDownPressurepsi RotationTorquelbft MovingSpeedfth   R squared = 0.20875
Depthfeet PeakDownPressurepsi RotationTorquelbft SpecificEnergyftlbft3   R squared = 0.23503
Depthfeet PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth   R squared = 0.1956
Depthfeet PeakDownPressurepsi RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.23422
Depthfeet PeakDownPressurepsi MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.21242
Depthfeet RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.17801
Depthfeet RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.2398
Depthfeet RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.23098
Depthfeet RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.22589
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.21175
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.23483
PeakDownPressurepsi RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.22344
PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.21992
RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.23374

---- Number of combinations = 5
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.22542
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.24526
Depthfeet PeakDownPressurepsi RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.23722
Depthfeet PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.23624
Depthfeet RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.24473
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.23686

---- Number of combinations = 6
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.24738

Appendix C – MLR – Unit Weight

------- MLR ---------

---> Target = UnitWeightpcf

---- Number of combinations = 1
Depthfeet R squared = 0.19272
PeakDownPressurepsi R squared = 0.046071
RotationTorquelbft R squared = 0.025197
RotationSpeedrevmin R squared = 0.010595
MovingSpeedfth R squared = 7.9056e-05
SpecificEnergyftlbft3 R squared = 0.11669

---- Number of combinations = 2
Depthfeet PeakDownPressurepsi R squared = 0.2533
Depthfeet RotationTorquelbft R squared = 0.19352
Depthfeet RotationSpeedrevmin R squared = 0.19652
Depthfeet MovingSpeedfth R squared = 0.1965
Depthfeet SpecificEnergyftlbft3 R squared = 0.27739
PeakDownPressurepsi RotationTorquelbft R squared = 0.10551
PeakDownPressurepsi RotationSpeedrevmin R squared = 0.084097
PeakDownPressurepsi MovingSpeedfth R squared = 0.047597
PeakDownPressurepsi SpecificEnergyftlbft3 R squared = 0.13725
RotationTorquelbft RotationSpeedrevmin R squared = 0.025198
RotationTorquelbft MovingSpeedfth R squared = 0.026826
RotationTorquelbft SpecificEnergyftlbft3 R squared = 0.14058
RotationSpeedrevmin MovingSpeedfth R squared = 0.01095
RotationSpeedrevmin SpecificEnergyftlbft3 R squared = 0.13298
MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.11794

---- Number of combinations = 3
Depthfeet PeakDownPressurepsi RotationTorquelbft R squared = 0.25658
Depthfeet PeakDownPressurepsi RotationSpeedrevmin R squared = 0.25424
Depthfeet PeakDownPressurepsi MovingSpeedfth R squared = 0.25419
Depthfeet PeakDownPressurepsi SpecificEnergyftlbft3 R squared = 0.27754
Depthfeet RotationTorquelbft RotationSpeedrevmin R squared = 0.1966
Depthfeet RotationTorquelbft MovingSpeedfth R squared = 0.19666
Depthfeet RotationTorquelbft SpecificEnergyftlbft3 R squared = 0.27765
Depthfeet RotationSpeedrevmin MovingSpeedfth R squared = 0.19891
Depthfeet RotationSpeedrevmin SpecificEnergyftlbft3 R squared = 0.27805
Depthfeet MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.28634
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin R squared = 0.10942

PeakDownPressurepsi RotationTorquelbft MovingSpeedfth   R squared = 0.10629
PeakDownPressurepsi RotationTorquelbft SpecificEnergyftlbft3   R squared = 0.14379
PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth   R squared = 0.084133
PeakDownPressurepsi RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.14022
PeakDownPressurepsi MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.15104
RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.026853
RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.14192
RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.14791
RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.13835

---- Number of combinations = 4
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin   R squared = 0.25658
Depthfeet PeakDownPressurepsi RotationTorquelbft MovingSpeedfth   R squared = 0.25853
Depthfeet PeakDownPressurepsi RotationTorquelbft SpecificEnergyftlbft3   R squared = 0.27837
Depthfeet PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth   R squared = 0.25556
Depthfeet PeakDownPressurepsi RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.27893
Depthfeet PeakDownPressurepsi MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.2902
Depthfeet RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.19921
Depthfeet RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.27805
Depthfeet RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.28643
Depthfeet RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.28635
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.11055
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.14425
PeakDownPressurepsi RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.15734
PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.154
RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.15007

---- Number of combinations = 5
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth   R squared = 0.25855
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin SpecificEnergyftlbft3   R squared = 0.27917
Depthfeet PeakDownPressurepsi RotationTorquelbft MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.29108
Depthfeet PeakDownPressurepsi RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.29157
Depthfeet RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.28653
PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3   R squared = 0.15784

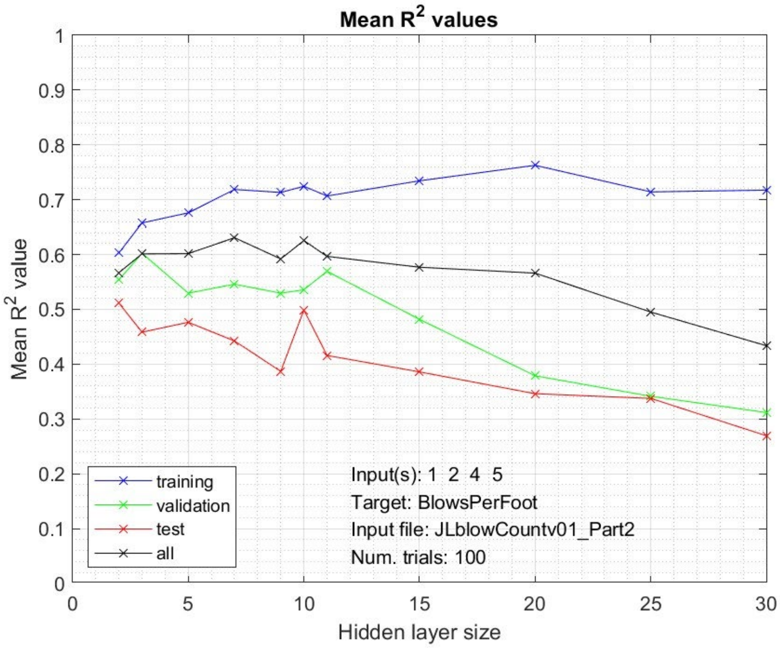
---- Number of combinations = 6
Depthfeet PeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3 R squared = 0.29184

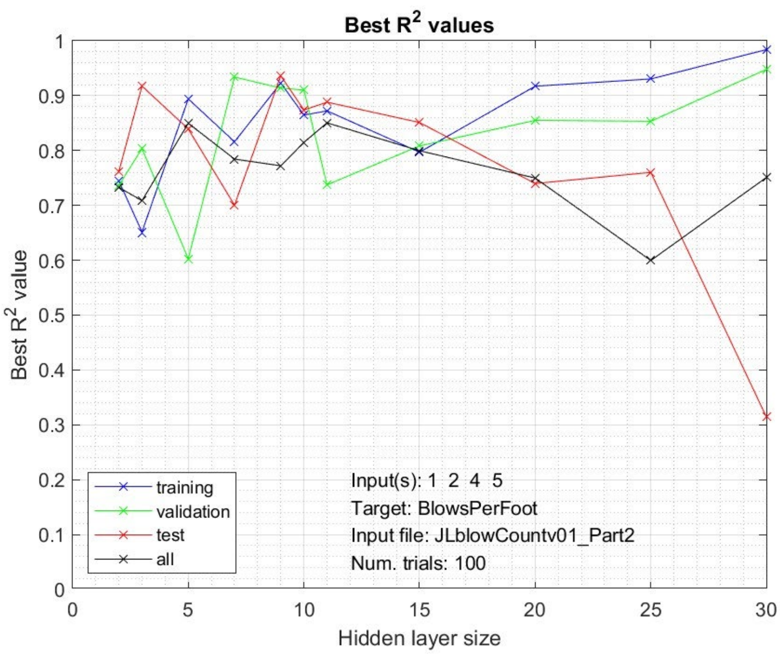
Appendix D – NN Modeling for SPT Blow Count: Mean R^2 and Best R^2 from 100 Iterations for Six Best Models

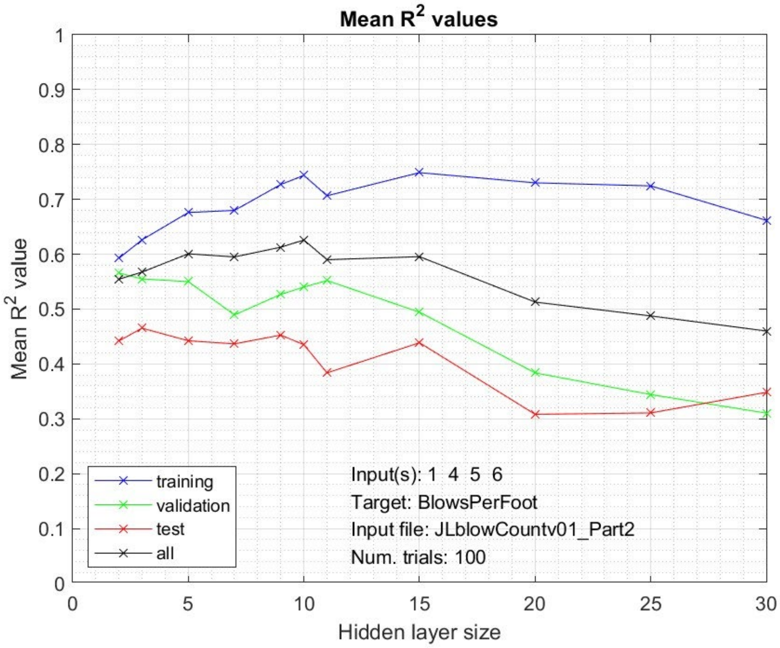
The inset text on each plot shows the training input number code, the training target, input file name (for reference) and the number of modeling iterations (trials). The legend on the plots is color coded for the data sets: blue for training, green for validation, red for testing and black for all.

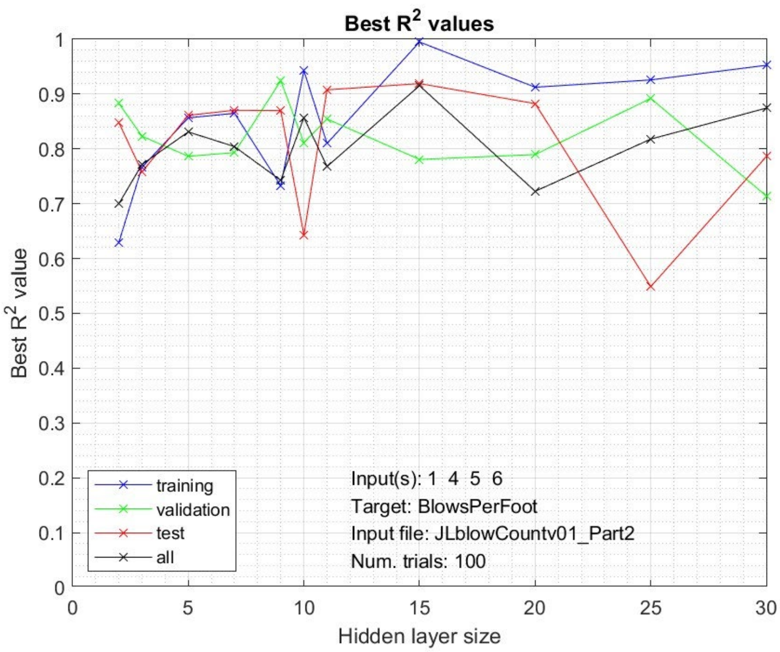
Appendix D-1 – Plots of Mean and Best R^2 Values for SPT Blow Counts

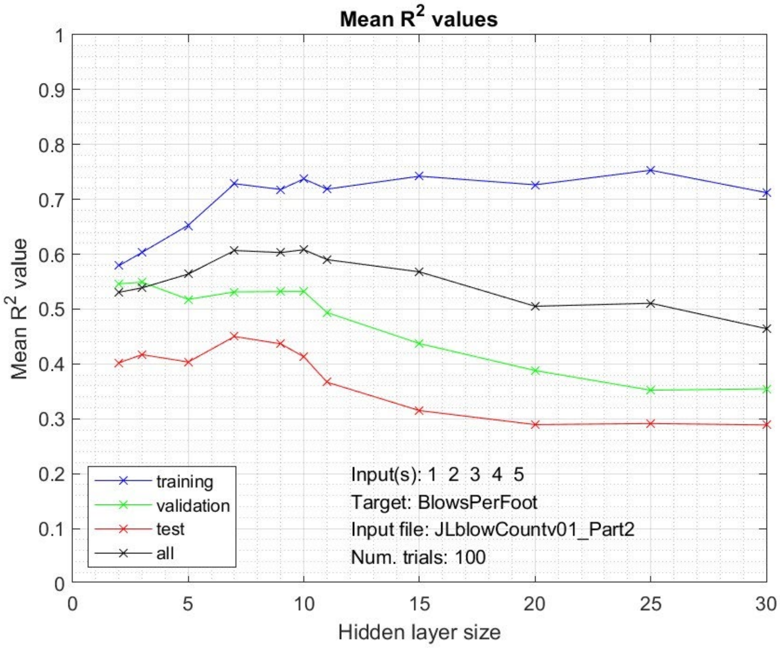
Results for NN modeling of SPT blow counts. Five pairs of plots are shown for the six best models listed in Table 12.

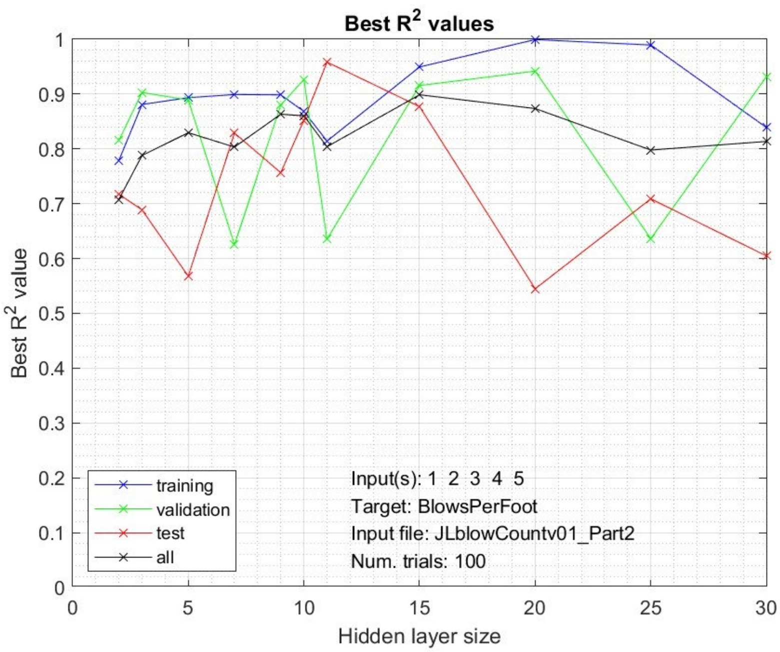


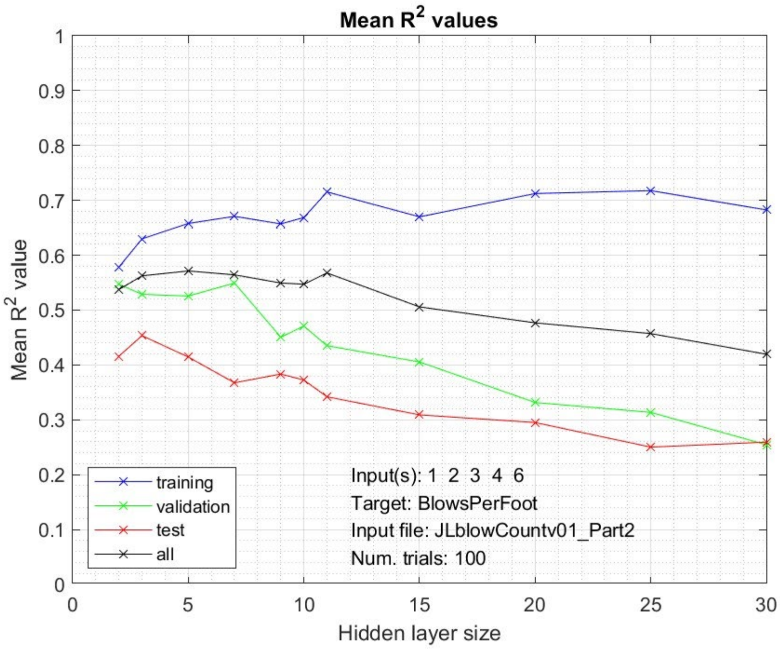


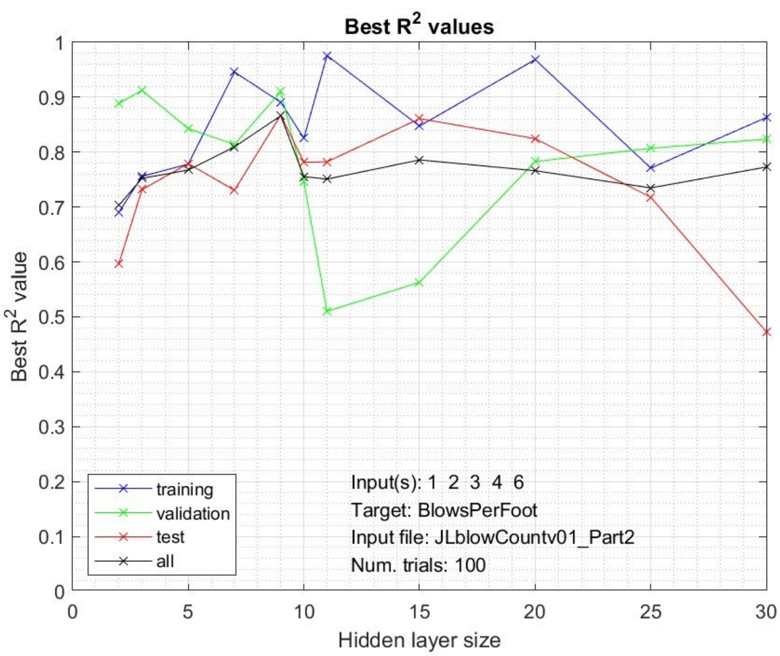

Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 4 5 6
Target: BlowsPerFoot
Input file: JLblowCountv01_Part2
Num. trials: 100

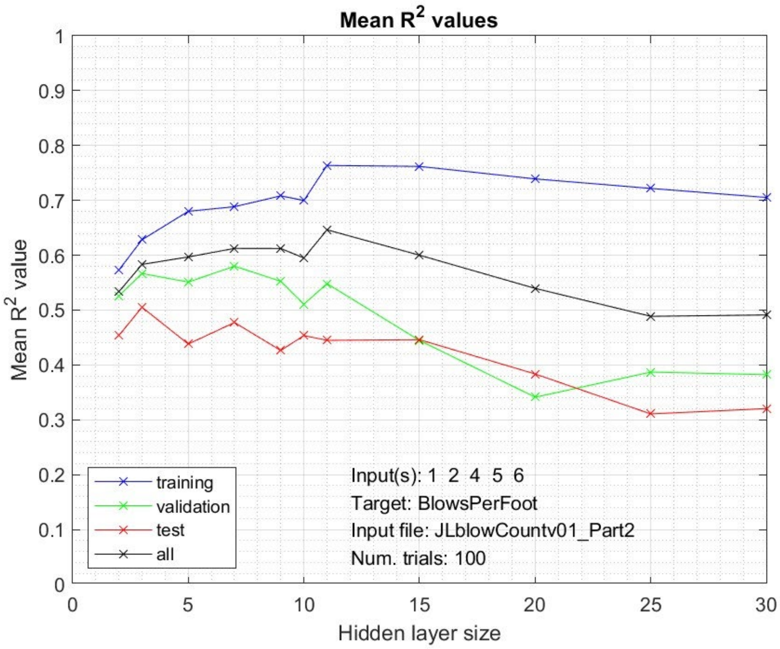

Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 4 5 6
Target: BlowsPerFoot
Input file: JLblowCountv01_Part2
Num. trials: 100

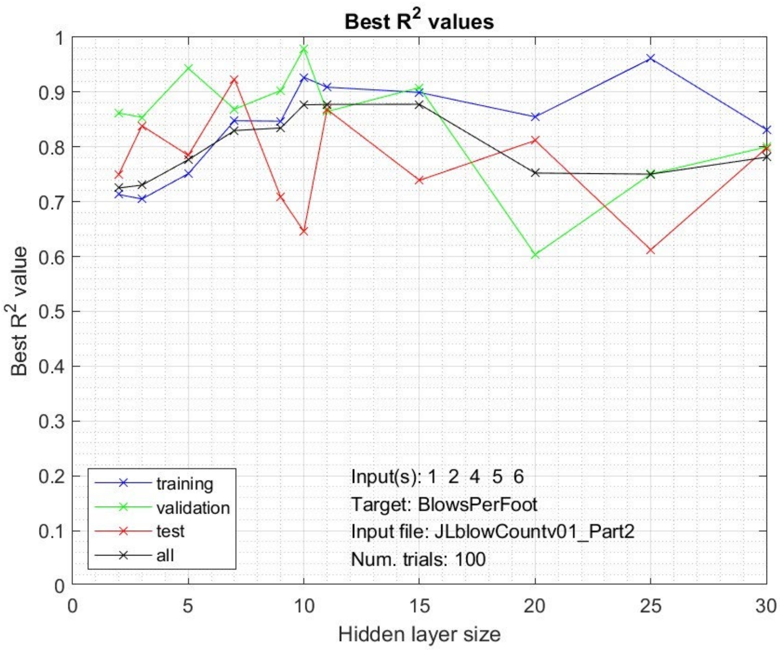

Mean R2 values
Mean R2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 3 4 5
Target: BlowsPerFoot
Input file: JLblowCountv01_Part2
Num. trials: 100


Best R2 values
Best R2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 3 4 5
Target: BlowsPerFoot
Input file: JLblowCountv01_Part2
Num. trials: 100


Mean R2 values
Mean R2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 3 4 6
Target: BlowsPerFoot
Input file: JLblowCountv01_Part2
Num. trials: 100


Best R2 values
Best R2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 3 4 6
Target: BlowsPerFoot
Input file: JLblowCountv01_Part2
Num. trials: 100


Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 4 5 6
Target: BlowsPerFoot
Input file: JLblowCountv01_Part2
Num. trials: 100


Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 4 5 6
Target: BlowsPerFoot
Input file: JLblowCountv01_Part2
Num. trials: 100

Appendix D-2 – Mean and Best R^2 Results in Text Form for SPT Blow Counts

Results for NN modelling of SPT blow counts showing results for the six best NN models.

inp	=	1	2	4	5		
--->	Input(s)	=	Depthfeet	PeakDownPressurepsi	RotationSpeedrevmin	MovingSpeedfth	
	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
Mean R	=						
	2	0.56688	0.6028	0.55371	0.51149		
	3	0.60124	0.65773	0.60232	0.45842		
	5	0.60169	0.67605	0.52959	0.47642		
	7	0.63067	0.71867	0.54594	0.44241		
	9	0.59203	0.71327	0.52948	0.38692		
	10	0.625494	0.724467	0.535856	0.498885		
	11	0.596638	0.70677	0.569383	0.41594		
	15	0.576854	0.734512	0.481786	0.385983		
	20	0.566077	0.762825	0.378829	0.346146		
	25	0.495042	0.714279	0.341465	0.337571		
	30	0.433693	0.717525	0.311769	0.269431		
BestR	=						
	2	0.73284	0.74441	0.73646	0.76193	2.9756	
	3	0.70847	0.65152	0.8035	0.91738	3.0809	
	5	0.8497	0.89405	0.60257	0.83923	3.1856	
	7	0.78438	0.81594	0.93394	0.70031	3.2346	
	9	0.77216	0.92302	0.91381	0.93609	3.5451	
	10	0.814826	0.86456	0.910245	0.873964	3.46359	
	11	0.850421	0.872267	0.737422	0.888129	3.34824	
	15	0.799636	0.796908	0.80838	0.851063	3.25599	
	20	0.749859	0.917255	0.85494	0.739854	3.26191	
	25	0.599554	0.930434	0.853318	0.760191	3.1435	
	30	0.750925	0.983939	0.947946	0.314096	2.99691	
inp	=	1	4	5	6		
--->	Input(s)	=	Depthfeet	RotationSpeedrevmin	MovingSpeedfth	SpecificEnergyftlbft3	
	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
Mean R	=						
	2	0.55444	0.59262	0.56579	0.44191		
	3	0.56748	0.62625	0.55499	0.46526		
	5	0.6008	0.67607	0.55012	0.4423		
	7	0.59515	0.67996	0.48948	0.43668		
	9	0.6128	0.7271	0.52685	0.45262		
	10	0.625948	0.743716	0.540184	0.435125		
	11	0.590069	0.706629	0.552058	0.383818		
	15	0.595574	0.748739	0.49437	0.438679		

		20	0.512768	0.730131	0.383746	0.308186	
		25	0.487565	0.72458	0.344208	0.310793	
		30	0.460058	0.661762	0.310391	0.348316	
BestR	=						
		2	0.70009	0.62949	0.88298	0.84811	3.0607
		3	0.77175	0.76655	0.82311	0.75807	3.1195
		5	0.83098	0.85667	0.78645	0.86122	3.3353
		7	0.80418	0.86493	0.79326	0.87045	3.3328
		9	0.74272	0.73283	0.92433	0.86993	3.2698
		10	0.857169	0.942793	0.811351	0.643121	3.25443
		11	0.767863	0.809854	0.854536	0.907775	3.34003
		15	0.915271	0.99503	0.780809	0.919126	3.61023
		20	0.722696	0.912494	0.789688	0.882624	3.3075
		25	0.817902	0.925863	0.892106	0.548734	3.18461
		30	0.874452	0.952563	0.713892	0.786234	3.32714
inp	=		1	2	3	4	5
--->	Input(s)	=		Depthfeet	PeakDownPr essurepsi	RotationTor quelbft	RotationSpe edrevmin	MovingSpe edfth
	HL	no.		all	train	val	test	Sum
	-----	---		-----	---	----	---------	
Mean R	=						
		2	0.53058	0.57904	0.54612	0.40207	
		3	0.5387	0.60332	0.54909	0.41704	
		5	0.56391	0.65293	0.51768	0.40356	
		7	0.60678	0.72855	0.53131	0.45008	
		9	0.60308	0.71813	0.5319	0.43668	
		10	0.608221	0.737321	0.531951	0.412957	
		11	0.590177	0.718684	0.493714	0.366782	
		15	0.567861	0.742266	0.437148	0.315016	
		20	0.505144	0.726558	0.387981	0.289501	
		25	0.510665	0.753123	0.352138	0.291461	
		30	0.464307	0.71226	0.354742	0.288934	
BestR	=						
		2	0.70783	0.77882	0.81514	0.71746	3.0192
		3	0.78791	0.88105	0.90297	0.68878	3.2607
		5	0.8295	0.8934	0.88931	0.5678	3.18
		7	0.80336	0.89923	0.62528	0.82879	3.1567
		9	0.86332	0.89856	0.87976	0.75654	3.3982
		10	0.860339	0.868422	0.926853	0.852136	3.50775
		11	0.804035	0.814216	0.63521	0.958332	3.21179
		15	0.898764	0.949395	0.915523	0.8771	3.64078
		20	0.873582	0.999477	0.94193	0.544816	3.3598
		25	0.79794	0.989442	0.636168	0.708876	3.13243
		30	0.813625	0.83898	0.931768	0.604696	3.18907
inp	=		1	2	3	4	6
--->	Input(s)	=		Depthfeet	PeakDownPr essurepsi	RotationTor quelbft	RotationSpe edrevmin	SpecificEne rgyftlbft3

	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
Mean R	=						
	2	0.53753	0.57832	0.54708	0.41594		
	3	0.56248	0.62983	0.52877	0.45344		
	5	0.57136	0.65796	0.52566	0.41447		
	7	0.56426	0.6709	0.54921	0.36746		
	9	0.54944	0.65717	0.45073	0.38349		
	10	0.547177	0.668745	0.470812	0.372511		
	11	0.567688	0.715419	0.435057	0.341982		
	15	0.505829	0.670055	0.405403	0.309037		
	20	0.476797	0.712486	0.33157	0.295064		
	25	0.457154	0.717743	0.3136	0.250269		
	30	0.419561	0.682634	0.254522	0.259345		
BestR	=						
	2	0.70325	0.6904	0.88875	0.59687	2.8793	
	3	0.75222	0.75591	0.91261	0.73178	3.1525	
	5	0.76743	0.77822	0.8427	0.77903	3.1674	
	7	0.8097	0.94584	0.81421	0.73049	3.3002	
	9	0.86618	0.89075	0.91019	0.86744	3.5346	
	10	0.755302	0.825282	0.746032	0.781528	3.10814	
	11	0.750913	0.975963	0.510014	0.782477	3.01937	
	15	0.785796	0.847465	0.562956	0.861024	3.05724	
	20	0.766173	0.968534	0.782872	0.824503	3.34208	
	25	0.734848	0.770924	0.806976	0.71784	3.03059	
	30	0.772921	0.86314	0.823844	0.472467	2.93237	
inp	=	1	2	4	5	6	
--->	Input(s)	=	Depthfeet	PeakDownPressurepsi	RotationSpeedrevmin	MovingSpeedfth	SpecificEnergyftlbft3
	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
Mean R	=						
	2	0.53348	0.573	0.52588	0.45373		
	3	0.58333	0.62821	0.56674	0.50524		
	5	0.59688	0.68008	0.55108	0.43818		
	7	0.61242	0.68851	0.58007	0.47741		
	9	0.61232	0.70822	0.55254	0.42641		
	10	0.594963	0.699755	0.510806	0.453596		
	11	0.646336	0.763646	0.548237	0.44483		
	15	0.60009	0.761969	0.444649	0.446075		
	20	0.539563	0.739141	0.341263	0.383575		
	25	0.488689	0.721812	0.387022	0.310765		
	30	0.491162	0.705274	0.382269	0.320449		
BestR	=						
	2	0.72508	0.71313	0.86181	0.75007	3.0501	
	3	0.73029	0.70499	0.85387	0.83852	3.1277	

5	0.77658	0.75105	0.9434	0.78458	3.2556
7	0.82981	0.84773	0.8688	0.92349	3.4698
9	0.83455	0.84694	0.90292	0.70815	3.2926
10	0.876638	0.926911	0.979241	0.645889	3.42868
11	0.877473	0.908914	0.864492	0.868317	3.5192
15	0.877706	0.899344	0.908213	0.739036	3.4243
20	0.752313	0.854844	0.603535	0.81169	3.02238
25	0.750315	0.960966	0.750458	0.612398	3.07414
30	0.781279	0.831647	0.799869	0.797835	3.21063

Elapsed time is 102.6447 minutes.

Training INPUTS: 1 2 3 4 5 6

DepthfeetPeakDownPressurepsi RotationTorquelbft RotationSpeedrevmin MovingSpeedfth SpecificEnergyftlbft3

Training TARGETS: 7

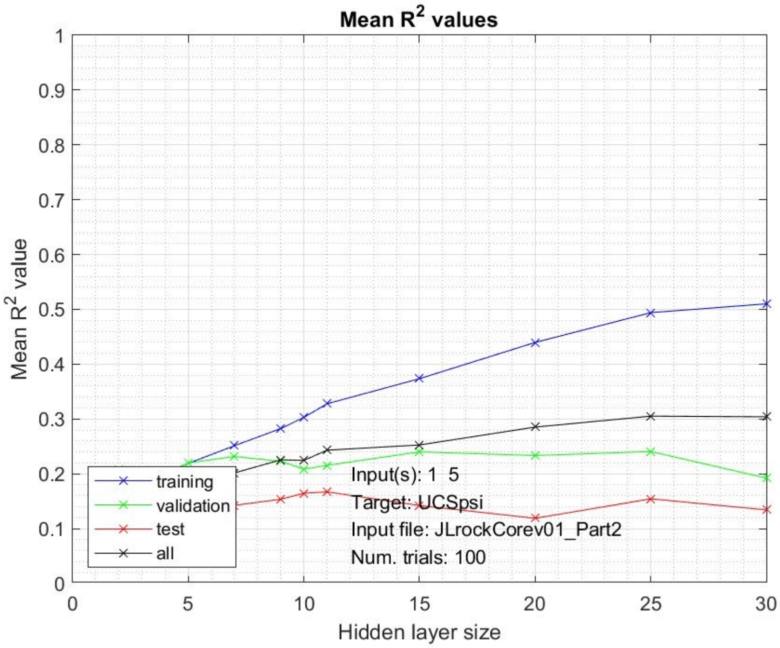
BlowsPerFoot

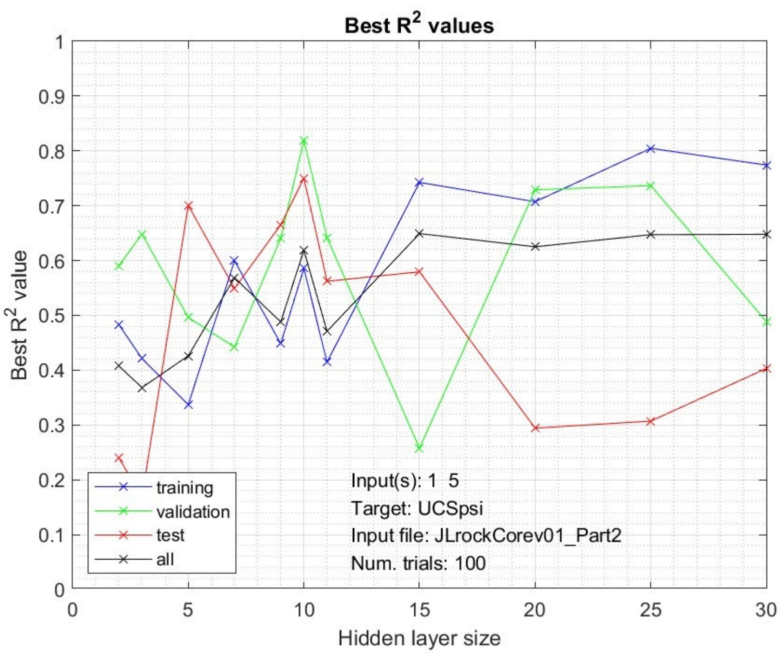
Appendix E – NN Modeling for UCS: Mean R^2 and Best R^2 from 100 Iterations for Four Best Models

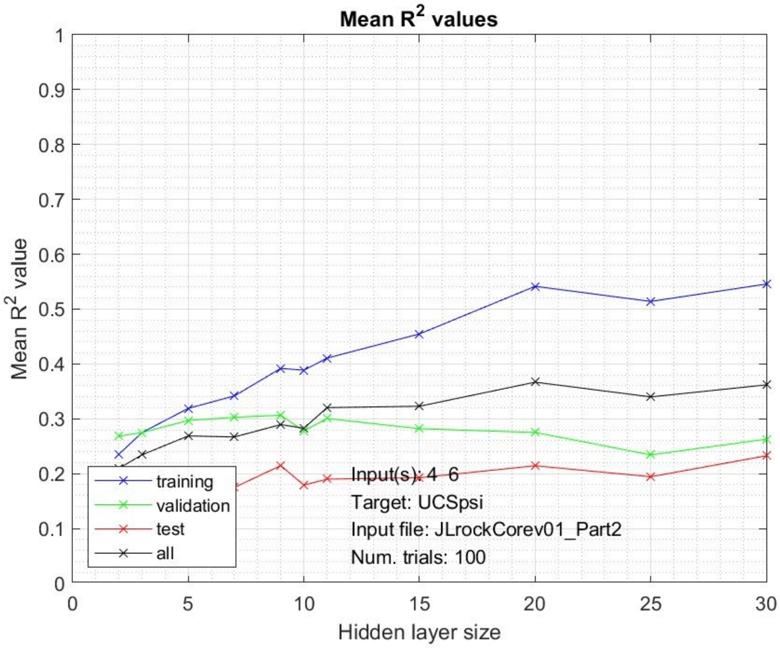
The inset text on each plot shows the training input number code, the training target, input file name (for reference) and the number of modeling iterations (trials). The legend on the plots is color coded for the data sets: blue for training, green for validation, red for testing and black for all.

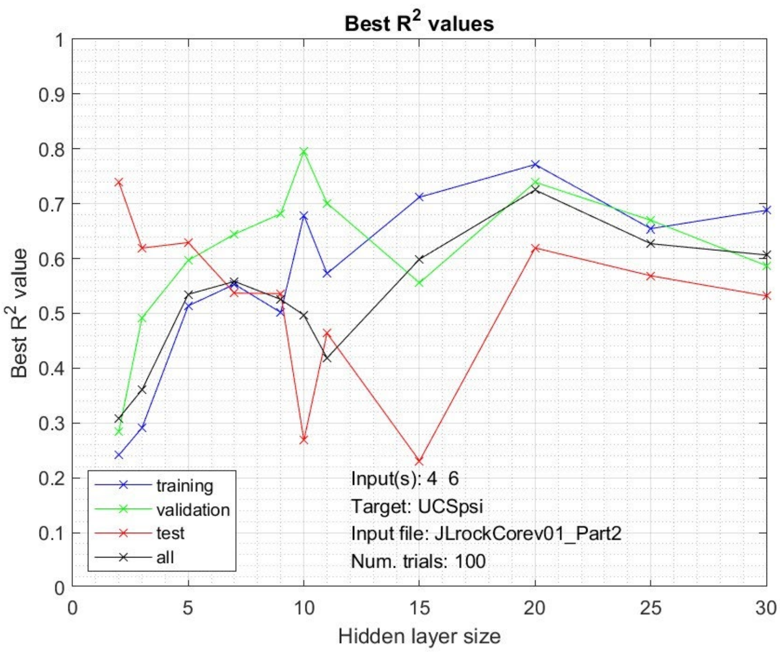
Appendix E-1 – Plots of Mean and Best R^2 Values for UCS

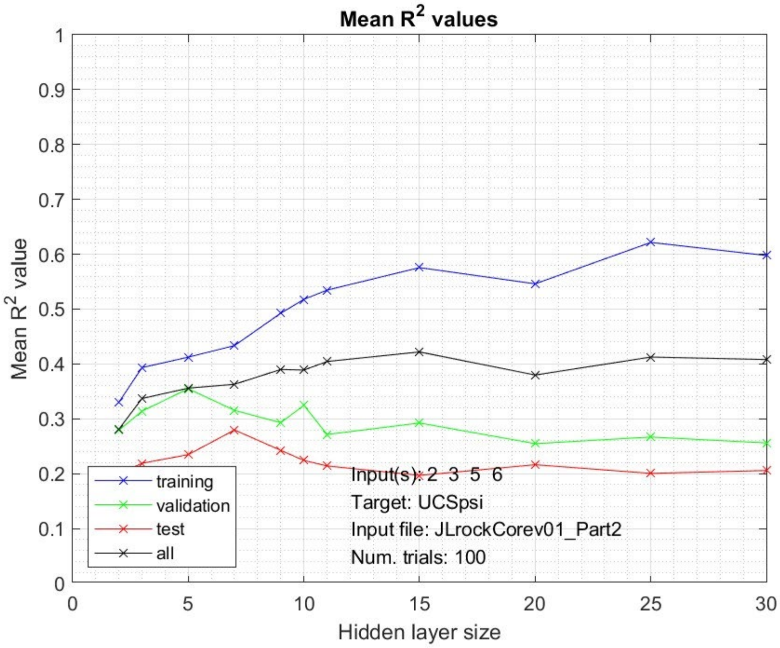
Results for NN modeling of UCS. Four pairs of plots are shown for the four best models listed in Table 13.



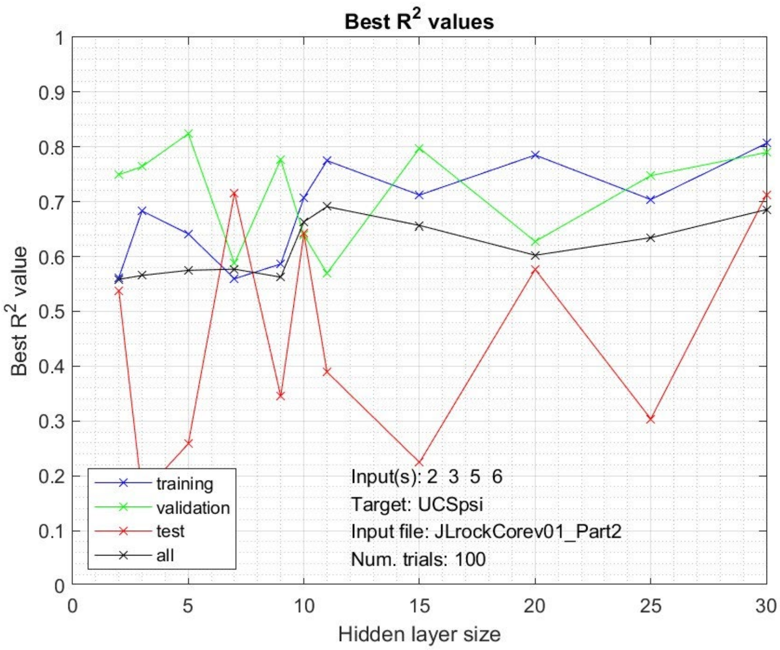



Mean R2 values
Mean R2 value
Hidden layer size
training
validation
test
all
Input(s): 4 6
Target: UCSpsi
Input file: JLrockCorev01_Part2
Num. trials: 100

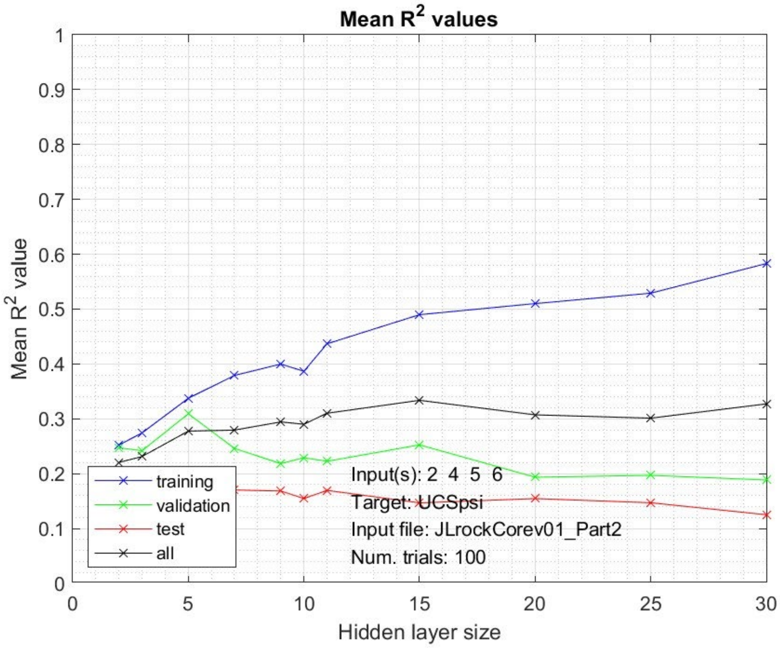

Best R2 values
Best R2 value
Hidden layer size
training
validation
test
all
Input(s): 4 6
Target: UCSpsi
Input file: JLrockCorev01_Part2
Num. trials: 100

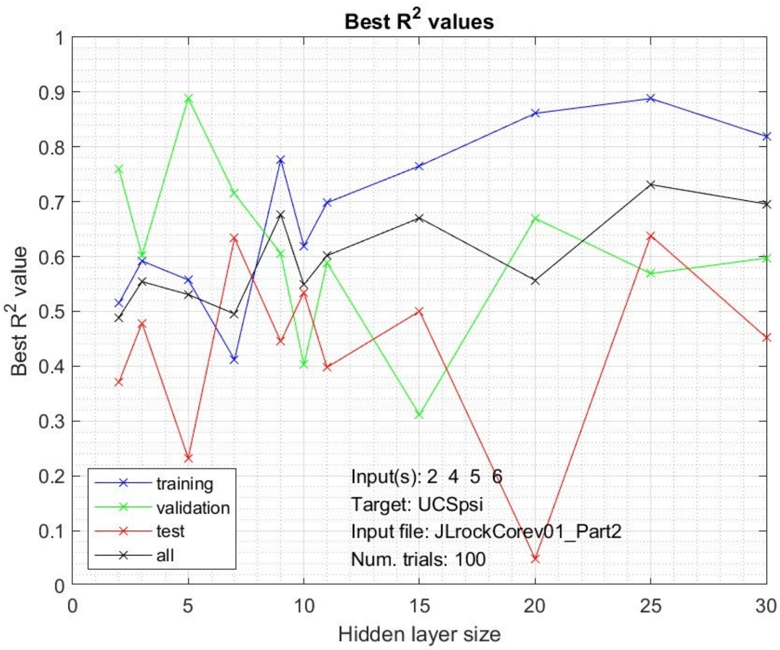


Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 2 3 5 6
Target: UCSpsi
Input file: JLrockCorev01_Part2
Num. trials: 100



Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 2 3 5 6
Target: UCSpsi
Input file: JLrockCorev01_Part2
Num. trials: 100


Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 2 4 5 6
Target: UCSpsi
Input file: JLrockCorev01_Part2
Num. trials: 100


Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 2 4 5 6
Target: UCSpsi
Input file: JLrockCorev01_Part2
Num. trials: 100

Appendix E-2 – Mean and Best R^2 Results in Text Form for UCS

Results for NN modelling of UCS showing results for the four best NN models.

inp	=	1	5				
--->	Input(s)	=	Depthfeet	MovingSpeedfth			
	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
MeanR	=						
	2	0.14817	0.17307	0.20817	0.14654		
	3	0.16245	0.18711	0.17795	0.17365		
	5	0.17243	0.21907	0.21998	0.13844		
	7	0.20173	0.25135	0.23156	0.14247		
	9	0.22547	0.28256	0.22294	0.15362		
	10	0.224485	0.302954	0.208562	0.164564		
	11	0.243122	0.32777	0.215464	0.167174		
	15	0.252648	0.373564	0.240111	0.142218		
	20	0.285285	0.439664	0.233478	0.118884		
	25	0.305218	0.493999	0.240698	0.154372		
	30	0.304035	0.510082	0.192162	0.134253		
BestR	=						
	2	0.40752	0.48301	0.59048	0.24003	1.721	
	3	0.36836	0.42108	0.64846	0.16869	1.6066	
	5	0.42614	0.33694	0.49613	0.70073	1.9599	
	7	0.5686	0.59954	0.44214	0.54903	2.1593	
	9	0.48797	0.44826	0.64065	0.66533	2.2422	
	10	0.618917	0.585845	0.819264	0.750203	2.77423	
	11	0.470959	0.414563	0.641698	0.562136	2.08936	
	15	0.649151	0.742529	0.257618	0.579419	2.22872	
	20	0.62509	0.707287	0.729021	0.294269	2.35567	
	25	0.647176	0.804657	0.736639	0.307148	2.49562	
	30	0.647843	0.774119	0.488563	0.403188	2.31371	
inp	=	4	6				
--->	Input(s)	=	RotationSpeedrevmin	SpecificEnergyftlbft3			
	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
MeanR	=						
	2	0.2098	0.23543	0.26843	0.19276		
	3	0.23437	0.27492	0.27487	0.18204		
	5	0.26885	0.31906	0.29711	0.18902		
	7	0.26699	0.34188	0.3027	0.17503		
	9	0.28952	0.39195	0.30656	0.21479		
	10	0.28275	0.388613	0.277874	0.179107		
	11	0.320392	0.410616	0.30059	0.190196		
	15	0.32296	0.454814	0.281998	0.192638		
	20	0.366799	0.541515	0.275118	0.2144		
	25	0.339999	0.513995	0.234347	0.194418		
	30	0.361877	0.545663	0.262851	0.232729		

BestR	=							
		2	0.30894	0.24148	0.2843	0.73908	1.5738	
		3	0.36048	0.29109	0.49184	0.61903	1.7624	
		5	0.5348	0.51377	0.5967	0.62919	2.2745	
		7	0.55826	0.55303	0.64449	0.53696	2.2927	
		9	0.52545	0.50167	0.68184	0.53604	2.245	
		10	0.496635	0.678916	0.794926	0.268258	2.23874	
		11	0.418593	0.572719	0.701098	0.46374	2.15615	
		15	0.598835	0.71187	0.555566	0.230823	2.09709	
		20	0.725063	0.77158	0.73916	0.619315	2.85512	
		25	0.627074	0.654556	0.669841	0.568576	2.52005	
		30	0.606464	0.688037	0.586968	0.531775	2.41324	
inp	=		2	3	5	6		
				PeakDownPress	RotationTorqu	MovingSpe	SpecificEnergyf	
--->	Input(s)		=	urepsi	elbft	edfth	tlbft3	
	HL		no.	all	train	val	test	Sum
	-----		---	-----	---	----	---------	
MeanR	=							
		2	0.28107	0.33008	0.2791	0.19978		
		3	0.33701	0.39338	0.31402	0.219		
		5	0.35596	0.4124	0.35484	0.23478		
		7	0.36294	0.4335	0.31541	0.27967		
		9	0.39004	0.49251	0.29301	0.24258		
		10	0.388888	0.517771	0.324743	0.224151		
		11	0.404463	0.534624	0.271494	0.214121		
		15	0.42189	0.575639	0.292419	0.196941		
		20	0.379817	0.546087	0.254771	0.216337		
		25	0.412553	0.621526	0.266848	0.20059		
		30	0.408044	0.597742	0.256034	0.20581		
BestR	=							
		2	0.55839	0.56164	0.7492	0.53815	2.4074	
		3	0.5655	0.68331	0.76402	0.16705	2.1799	
		5	0.57484	0.64146	0.824	0.25827	2.2986	
		7	0.57702	0.55949	0.58746	0.71615	2.4401	
		9	0.56241	0.58639	0.777	0.34486	2.2707	
		10	0.663276	0.707382	0.639098	0.642145	2.6519	
		11	0.691045	0.77489	0.569525	0.389317	2.42478	
		15	0.656798	0.712167	0.797553	0.224438	2.39096	
		20	0.602329	0.785058	0.627518	0.576475	2.59138	
		25	0.634393	0.703913	0.747585	0.303678	2.38957	
		30	0.685594	0.806519	0.789885	0.712658	2.99466	
inp	=		2	4	5	6		
				PeakDownPress	RotationSpeedr	MovingSpe	SpecificEnergyf	
--->	Input(s)		=	urepsi	evmin	edfth	tlbft3	
	HL		no.	all	train	val	test	Sum
	-----		---	-----	---	----	---------	
MeanR	=							
		2	0.22052	0.25224	0.24726	0.17195		

		3	0.23127	0.27426	0.2418	0.17333	
		5	0.27763	0.33748	0.30912	0.1578	
		7	0.27947	0.37913	0.24611	0.17031	
		9	0.29441	0.39982	0.21828	0.16842	
		10	0.29013	0.386672	0.229181	0.154725	
		11	0.310219	0.43679	0.222555	0.169587	
		15	0.333731	0.489839	0.252539	0.146798	
		20	0.307227	0.510065	0.193574	0.154642	
		25	0.301239	0.529052	0.196975	0.147009	
		30	0.327275	0.583058	0.188517	0.125177	
BestR	=						
		2	0.48884	0.51462	0.75968	0.37029	2.1334
		3	0.55422	0.59197	0.60211	0.47876	2.2271
		5	0.53071	0.55737	0.8888	0.23207	2.2089
		7	0.49537	0.41205	0.71483	0.63351	2.2558
		9	0.67638	0.77675	0.60543	0.44511	2.5037
		10	0.548596	0.619173	0.402624	0.534647	2.10504
		11	0.601691	0.6982	0.588494	0.397873	2.28626
		15	0.670379	0.765284	0.311241	0.500204	2.24711
		20	0.556653	0.861222	0.669703	0.048837	2.13642
		25	0.731169	0.888198	0.569004	0.638239	2.82661
		30	0.695765	0.819142	0.597166	0.452253	2.56433

Elapsed	time	is		92.7683	minutes.		

Training	INPUTS:		1	2	3	4	5	6
Depthfeet	PeakDownPressurepsi	RotationTorquelbft		RotationSpeedrevmin	MovingSpeedfth	SpecificEnergyftlbft3		

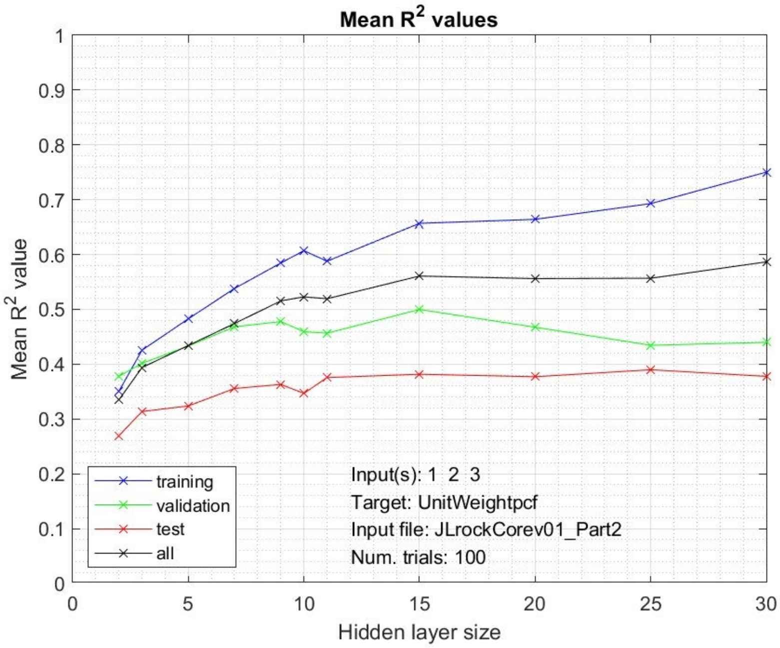
Training	TARGETS:		8				
UCSpsi							

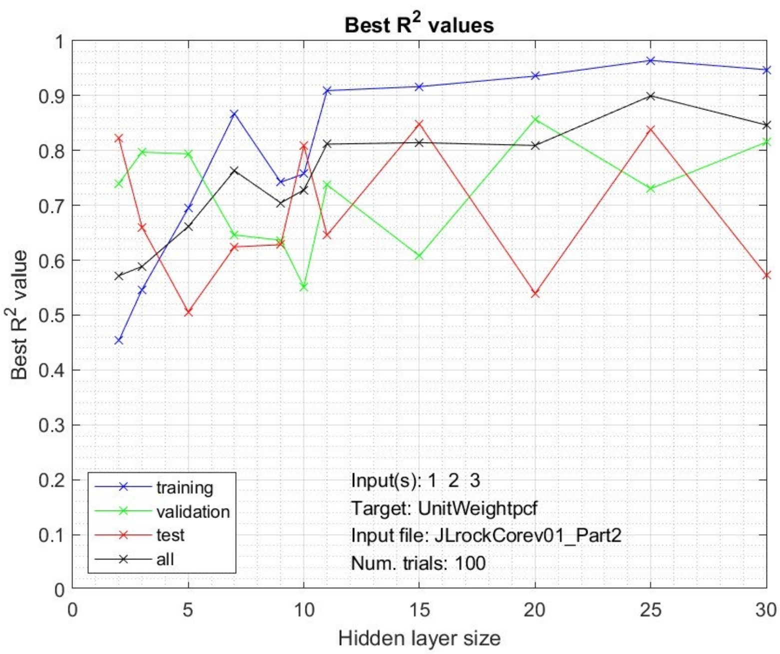
Appendix F – NN Modeling for Unit Weight: Mean R^2 and Best R^2 from 100 Iterations for Seven Best Models

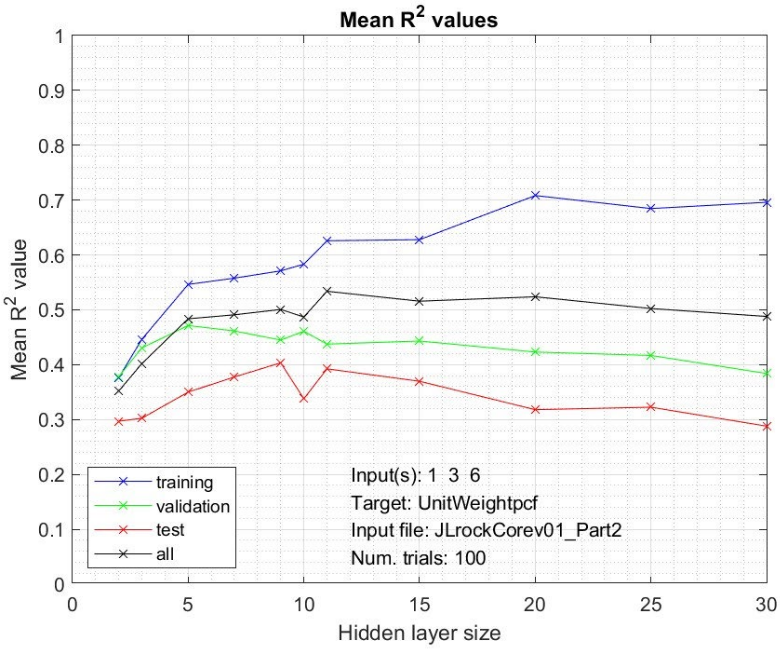
The inset text on each plot shows the training input number code, the training target, input file name (for reference) and the number of modeling iterations (trials). The legend on the plots is color coded for the data sets: blue for training, green for validation, red for testing and black for all.

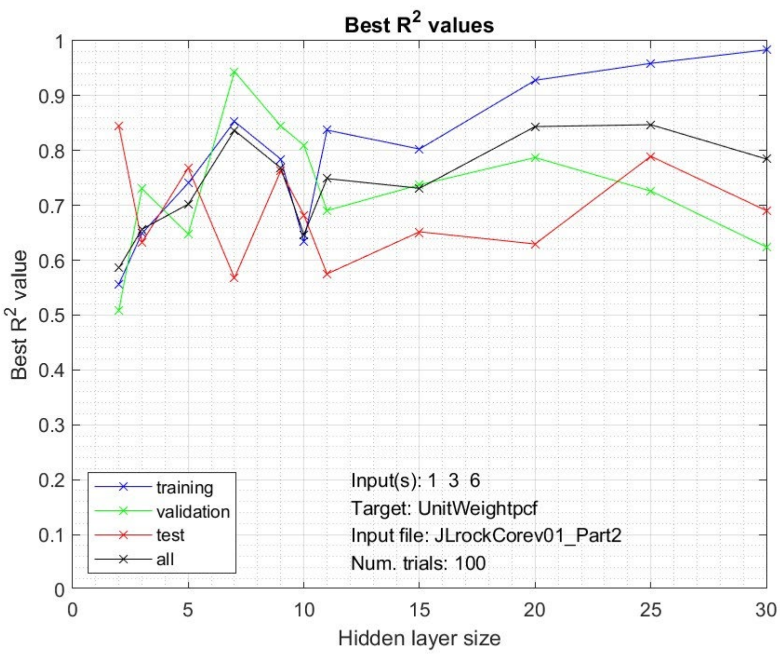
Appendix F-1 – Plots of Mean and Best R^2 Values for Unit Weight

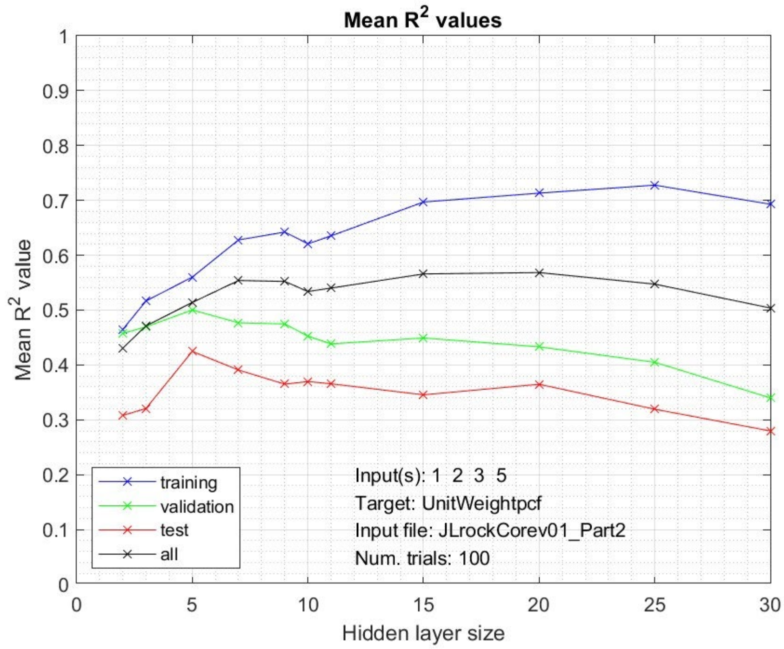
Results for NN modeling of Unit weight. Six pairs of plots are shown for the seven best models listed in Table 14.



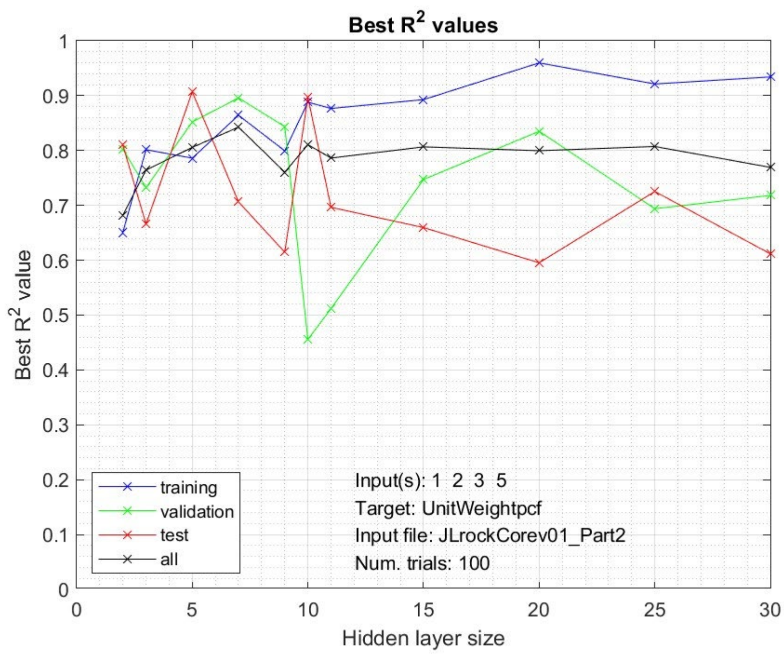



Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 3 6
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100

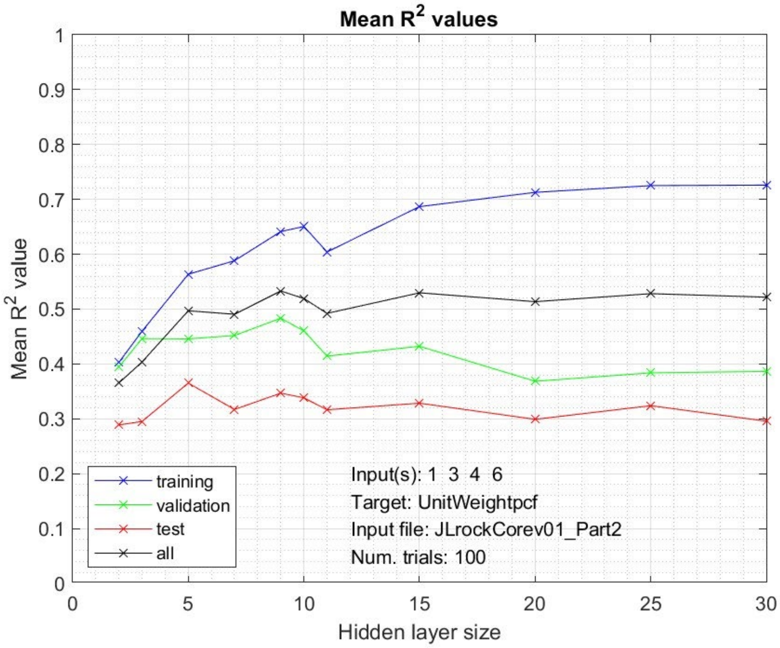

Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 3 6
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100

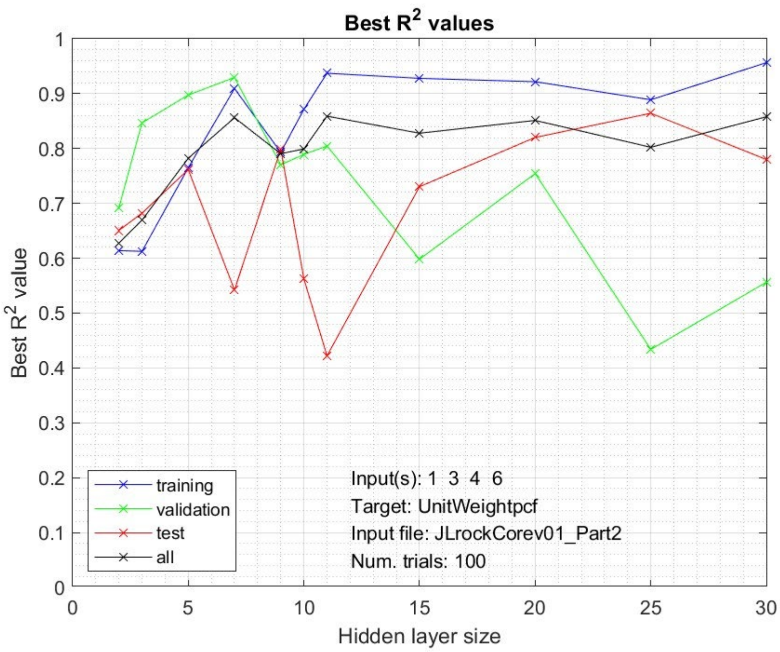


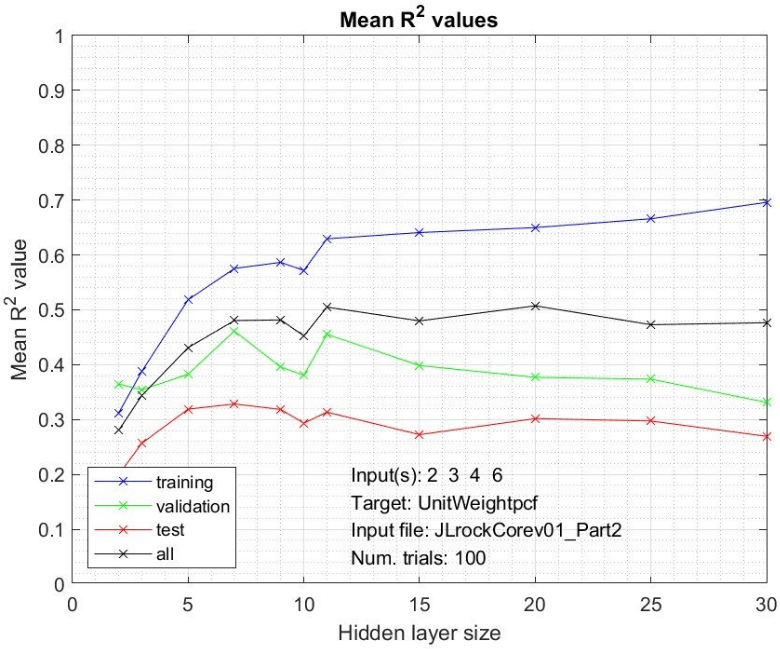
Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 3 5
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100

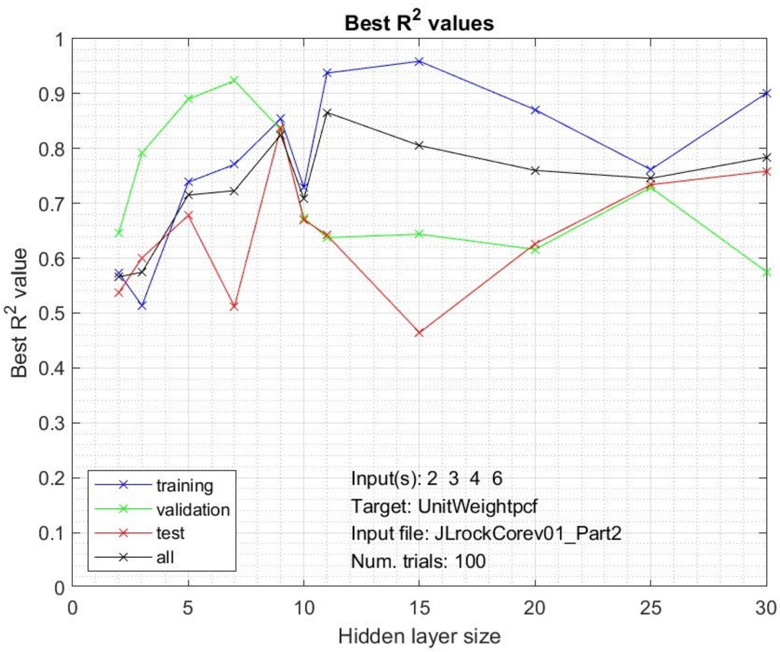


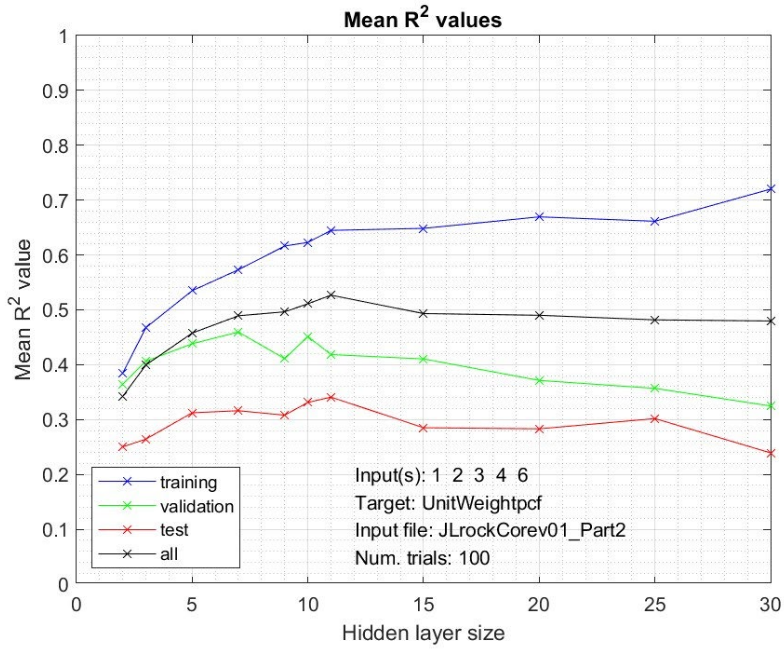
Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 3 5
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100

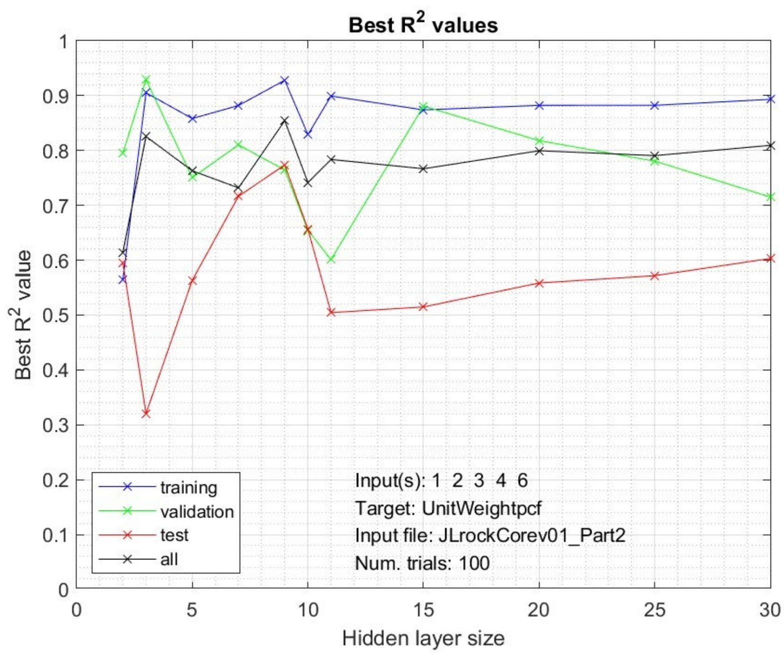

Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 3 4 6
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100


Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 3 4 6
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100


Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 2 3 4 6
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100


Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 2 3 4 6
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100


Mean R^2 values
Mean R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 3 4 6
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100


Best R^2 values
Best R^2 value
Hidden layer size
training
validation
test
all
Input(s): 1 2 3 4 6
Target: UnitWeightpcf
Input file: JLrockCorev01_Part2
Num. trials: 100

Appendix F-2 – Mean and Best R^2 Results in Text Form for Unit Weight

Results for NN modelling of Unit weight showing results for the seven best NN models.

inp	=	1	2	3			
--->	Input(s)	=	Depthfeet	PeakDownPressurepsi	RotationTorquelbft		
	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
Mean R	=						
	2	0.33491	0.35044	0.37796	0.26945		
	3	0.39385	0.42556	0.40152	0.31366		
	5	0.43402	0.48265	0.43306	0.3238		
	7	0.4742	0.53812	0.46818	0.35568		
	9	0.51543	0.58451	0.47771	0.36312		
	10	0.522798	0.607014	0.459239	0.346755		
	11	0.519381	0.587805	0.456551	0.37558		
	15	0.56082	0.656951	0.499778	0.381714		
	20	0.556045	0.664231	0.467391	0.377174		
	25	0.556763	0.692946	0.434527	0.389848		
	30	0.586679	0.750393	0.439845	0.377812		
BestR	=						
	2	0.57172	0.45344	0.73999	0.82232	2.5875	
	3	0.58869	0.54651	0.79697	0.66042	2.5926	
	5	0.66148	0.69477	0.79398	0.50583	2.6561	
	7	0.76311	0.86711	0.64587	0.62446	2.9006	
	9	0.7045	0.74221	0.63656	0.62825	2.7115	
	10	0.728293	0.757521	0.551672	0.808687	2.84617	
	11	0.811664	0.909211	0.737489	0.64583	3.10419	
	15	0.814322	0.916456	0.607903	0.848142	3.18682	
	20	0.809247	0.935659	0.856899	0.539647	3.14145	
	25	0.899728	0.96414	0.730662	0.838524	3.43305	
	30	0.846484	0.947291	0.815294	0.572523	3.18159	
inp	=	1	3	6			
--->	Input(s)	=	Depthfeet	RotationTorquelbft	SpecificEnergyftlbft3		
	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
Mean R	=						
	2	0.35194	0.37626	0.37843	0.29699		
	3	0.40205	0.4463	0.43053	0.30244		
	5	0.48371	0.54635	0.47146	0.35008		
	7	0.491	0.55782	0.46152	0.37768		
	9	0.5007	0.57104	0.44489	0.4035		
	10	0.487081	0.583324	0.461002	0.337877		
	11	0.533875	0.625933	0.437568	0.392465		
	15	0.515778	0.627953	0.443187	0.369831		

		20	0.523846	0.708357	0.423123	0.318077	
		25	0.502425	0.684657	0.416861	0.322592	
		30	0.487976	0.696068	0.383965	0.287991	
BestR	=						
		2	0.58604	0.55625	0.50812	0.84507	2.4955
		3	0.65662	0.64912	0.73022	0.63263	2.6686
		5	0.70225	0.74059	0.64756	0.7682	2.8586
		7	0.83668	0.85293	0.94376	0.5677	3.2011
		9	0.76812	0.78433	0.8446	0.76273	3.1598
		10	0.646847	0.634175	0.809587	0.682459	2.77307
		11	0.748859	0.837168	0.690605	0.575045	2.85168
		15	0.731159	0.802731	0.737569	0.65182	2.92328
		20	0.84366	0.928059	0.787175	0.629643	3.18854
		25	0.84706	0.958907	0.726187	0.789453	3.32161
		30	0.784532	0.983571	0.624153	0.690435	3.08269
inp	=		1	2	3	5	
--->	Input(s)	=		Depthfeet	PeakDownPressurepsi	RotationTorquelbft	MovingSpeedfth
	HL	no.		all	train	val	test	Sum
	-----	---		-----	---	----	---------
Mean R	=						
		2	0.43079	0.4649	0.45754	0.30805	
		3	0.47135	0.51663	0.46949	0.32073	
		5	0.51394	0.56014	0.50023	0.42474	
		7	0.55399	0.62785	0.47692	0.39077	
		9	0.55226	0.64226	0.47483	0.36505	
		10	0.533887	0.620873	0.452474	0.369766	
		11	0.540181	0.635299	0.438378	0.36571	
		15	0.565939	0.697019	0.449206	0.345577	
		20	0.568397	0.713236	0.433048	0.364819	
		25	0.547363	0.72777	0.404874	0.319317	
		30	0.503788	0.692961	0.33993	0.279737	
BestR	=						
		2	0.6821	0.6507	0.80265	0.81006	2.9455
		3	0.7644	0.80156	0.73208	0.6659	2.9639
		5	0.80571	0.78606	0.85205	0.90697	3.3508
		7	0.84264	0.86427	0.89585	0.70633	3.3091
		9	0.76052	0.79939	0.84355	0.61461	3.0181
		10	0.810695	0.888103	0.455599	0.896888	3.05129
		11	0.786281	0.876718	0.511804	0.69647	2.87127
		15	0.806641	0.892763	0.747211	0.659577	3.10619
		20	0.799676	0.959785	0.835024	0.595404	3.18989
		25	0.807344	0.92132	0.693934	0.72529	3.14789
		30	0.769304	0.934165	0.718265	0.611597	3.03333
inp	=		1	3	4	6	
--->	Input(s)	=		Depthfeet	RotationTorquelbft	RotationSpeedrevmin	SpecificEnergyftlbft3

	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
Mean R	=						
		2	0.36535	0.40286	0.39438	0.28887	
		3	0.40356	0.45957	0.44624	0.29515	
		5	0.49696	0.56353	0.4457	0.36515	
		7	0.49061	0.5882	0.45185	0.31707	
		9	0.533	0.6413	0.4834	0.34681	
		10	0.519377	0.650656	0.460206	0.338251	
		11	0.492207	0.604156	0.414357	0.316505	
		15	0.529702	0.686808	0.432179	0.328518	
		20	0.513556	0.712835	0.368452	0.299107	
		25	0.528135	0.7251	0.383821	0.323961	
		30	0.521765	0.725954	0.386419	0.295689	
BestR	=						
		2	0.62771	0.61386	0.69154	0.65059	2.5837
		3	0.66933	0.61256	0.84681	0.6822	2.8109
		5	0.78232	0.76488	0.8975	0.76172	3.2064
		7	0.85617	0.90936	0.92956	0.54199	3.2371
		9	0.79045	0.79291	0.77037	0.79894	3.1527
		10	0.799346	0.871498	0.789236	0.562487	3.02257
		11	0.858932	0.937218	0.804533	0.421986	3.02267
		15	0.827914	0.927894	0.598201	0.730467	3.08448
		20	0.851243	0.921801	0.754332	0.820176	3.34755
		25	0.802296	0.888845	0.433802	0.86426	2.9892
		30	0.857923	0.956515	0.556421	0.779902	3.15076
inp	=		2	3	4	6	
--->	Input(s)	=	PeakDownPressurepsi	RotationTorquelbft	RotationSpeedrevmin	SpecificEnergyftlbft3	
	HL	no.	all	train	val	test	Sum
	-----	---	-----	---	----	---------	
Mean R	=						
		2	0.28043	0.312	0.36477	0.19984	
		3	0.34389	0.38797	0.35405	0.25686	
		5	0.43117	0.51841	0.38278	0.31907	
		7	0.48049	0.57539	0.46134	0.32847	
		9	0.48167	0.58662	0.39573	0.31848	
		10	0.452503	0.571806	0.380914	0.293566	
		11	0.50499	0.629527	0.45539	0.313526	
		15	0.479909	0.640908	0.398469	0.272552	
		20	0.507391	0.649963	0.376966	0.301776	
		25	0.472916	0.666065	0.373653	0.297397	
		30	0.476545	0.695948	0.331376	0.269457	
BestR	=						
		2	0.5663	0.57311	0.64682	0.53744	2.3237
		3	0.57453	0.51352	0.79182	0.60072	2.4806

		5	0.71514	0.73861	0.8898	0.678	3.0215	
		7	0.72324	0.771	0.92363	0.51192	2.9298	
		9	0.82455	0.85414	0.83427	0.83728	3.3502	
		10	0.708391	0.728953	0.67328	0.670004	2.78063	
		11	0.865724	0.937498	0.637614	0.642025	3.08286	
		15	0.805442	0.959059	0.643858	0.46429	2.87265	
		20	0.760081	0.8707	0.61603	0.626351	2.87316	
		25	0.745572	0.761514	0.72903	0.734042	2.97016	
		30	0.784146	0.900885	0.575438	0.758615	3.01908	
inp	=		1	2	3	4	6	
--->	Input(s)	=		Depthfeet	PeakDownPr essurepsi	RotationTor quelbft	RotationSpe edrevmin	SpecificEne rgyftlbft3
	HL	no.		all	train	val	test	Sum
	-----	---		-----	---	----	---------	
Mean R	=							
		2	0.34225	0.38435	0.36473	0.25032		
		3	0.39937	0.46748	0.40632	0.26438		
		5	0.45767	0.53493	0.43816	0.31238		
		7	0.48922	0.57317	0.45956	0.31617		
		9	0.49642	0.61633	0.41099	0.30803		
		10	0.511068	0.622906	0.45146	0.331262		
		11	0.526761	0.644825	0.418506	0.340923		
		15	0.49324	0.648547	0.410541	0.285133		
		20	0.490117	0.669505	0.371371	0.283178		
		25	0.481794	0.66149	0.356881	0.301818		
		30	0.479729	0.720106	0.324808	0.239271		
BestR	=							
		2	0.61457	0.56392	0.79472	0.59567	2.5689	
		3	0.82552	0.90528	0.92921	0.3204	2.9804	
		5	0.76301	0.85829	0.75048	0.56337	2.9352	
		7	0.73193	0.88202	0.81023	0.71662	3.1408	
		9	0.85439	0.92813	0.76439	0.77373	3.3206	
		10	0.741647	0.828848	0.654696	0.656633	2.88182	
		11	0.78369	0.899255	0.601222	0.504482	2.78865	
		15	0.766748	0.873975	0.880941	0.514889	3.03655	
		20	0.799591	0.882332	0.817939	0.558492	3.05835	
		25	0.790707	0.882414	0.780617	0.571875	3.02561	
		30	0.80939	0.893252	0.715077	0.603177	3.0209	
Elaps ed	time	is		108.575	minutes.			

Traini ng	INPUTS:		1	2	3	4	5	6
Dept hfeet	PeakDownPr essurepsi	RotationTo rquelbft		RotationSpe edrevmin	MovingSpee dfth	SpecificEnergyftlbft3		

Traini ng	TARGETS:	9
UnitWeightpcf		
