FLORIDA DEPARTMENT OF TRANSPORTATION
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Florida Method of Test
for
Measuring While Drilling (MWD)
for Geotechnical Applications

Designation: FM 5-625

1. Scope

This method describes the Measuring While Drilling (MWD) procedure to monitor and record drilling data during the drilling process for geotechnical applications. MWD is conducted using computerized systems with sensors placed on the drill rig to monitor a series of drilling parameters. The sensors continuously collect data for each monitored parameter, in real-time, without interfering with the drilling process. The monitored data typically are displayed in real-time and often recorded for further analysis. The continuous sampling produces high resolution profiles of individual and compound drilling parameters that can be used to quantify changes in subsurface conditions, assess geo-mechanical properties, as well as optimize drilling operations.

2. Drilling Equipment

Drill rigs and their accompanying equipment should be appropriately sized for the scope of the drilling application and MWD investigation. This includes a drill rig with sufficient power and stability to achieve the required drilling depth while maintaining a steady borehole; and drilling equipment such as drill rods, drill bits, and sensors that are robust enough to meet the demands of the drilling process while providing enough sensitivity to delineate changes in the subsurface strata via MWD. The drill rig should also allow accurate and timely adjustments of the controlled drilling parameters.

For drilling applications such as rock coring that require fluid injection to remove drilled debris, the pump must have the following characteristics:

- Provides a constant flow rate independent of the injection pressure
- Has a sensitive and calibrated pressure gauge mounted on the pump outflow
- Allows a 30 in/s to 40 in/s cuttings return (dependent upon the fluid viscosity)

Prior to each MWD test, the straightness of drill rods must be inspected. Deviation from linear shall not exceed a tenth of an inch from the centerline per five-foot section of rod. Drill rods that fail to meet this criterion should be marked and removed from further use. Failure to do so may induce eccentric rotation and excessive vibration which invalidates the MWD test.

3. Monitored Drilling Parameters

3.1 General

Drilling parameters are designated by one of the three categories.

1. Method based parameters – parameters that reflect the drilling application including type of drill rig, type of drilling tool, drill bit diameter, method of drilled debris removal, and drill rig limitations.
2. Controlled drilling parameters – parameters that are controlled by the drill rig operator including crowd, rotational speed, inclination, drilling slurry properties, and fluid injection flow rate.
3. Responsive drilling parameters – parameters that are dependent upon method-based parameters, controlled parameters, and the strata encountered during drilling which includes torque, penetration rate, vibration, and fluid injection pressure.

3.2 Drilling Parameters

- Torque
- Crowd or downward thrust
- Rotational speed
- Penetration rate
- Drilling fluid injection mass flow rate
- Drilling fluid injection volumetric flow rate
- Drilling fluid injection pressure
- Drilling fluid density
- Drilling fluid viscosity
- Drilling fluid temperature
- Vibration
- Inclination
- Eccentricity or eccentric rotation
- Direction of drilling rotation (CW or CCW)

3.3 Data Recording

3.3.1 Monitoring System

The monitoring system is comprised of a data acquisition module (DAQ), one or more junction boxes, and a series of individual sensors for each monitored drilling parameter. The drill rig battery provides power to the monitored system routed through the junction box. The junction box also routes the signals collected from each sensor to the DAQ module for real-time recording, assessment, and storage. The DAQ module should provide, or be routed to, a visual display that provides the monitored drilling parameters in a columnar format in which each parameter is referenced to the depth of measurement. The visual display should present the drilling parameters in order according to the owner's required format. If a required format is not provided by the owner, the following drilling parameter order is recommended: penetration rate, rotational speed, torque, crowd, injection flow rate, and injection pressure. Additional individual or compound parameters to be monitored in real-time should be displayed to the right side of the final required parameter displayed.

The data generated from the MWD test must be provided to the owner graphically (**Figure 3-1**) and in an electronic file using a comma-separated values (.csv) or Excel format (.xlsx). The tabular data included in the electronic file should present the parameters in the same order as the graphical display (**Table 3-1. Example of tabular data submitted to the owner.**)

For auger cast piles (ACP), Automated Monitoring Equipment (AME) systems are often used to record and report the MWD data in a time-referenced-format. Consequently, the tabular data is generated differently and must be provided to the owner in the following order with the units of measure identified: time stamp (mm/dd/yyyy hh:mm:ss AM/PM), duration (min), rotational speed (RPM), penetration rate (ft/min), penetration rate (min/ft), depth (ft), torque hydraulic pressure (psi), torque (ft-lb), crowd hydraulic pressure (psi), and crowd (lbf). In addition, the required grouting parameters must be provided to the owner in the following order with the units of measure identified: time stamp (mm/dd/yyyy hh:mm:ss AM/PM), duration (min), rotational speed (RPM), withdrawal rate (ft/min), withdrawal rate (min/ft), depth (ft), flow meter grout flow (CFM), flow meter grout volume (CF), grout factor, grout pressure (psi), pump stroke count, pump stroke flow rate (CFM), pump stroke volume (CF), cumulative GF stroke, and cumulative GF meter.

For drilled shaft and ACP applications, it is recommended to use a DAQ module that is capable of transmitting the MWD data wirelessly to an external computer for monitoring at a safe distance away from construction. This is intended to assist the Construction Engineering Inspector (CEI) during drilling and construction.

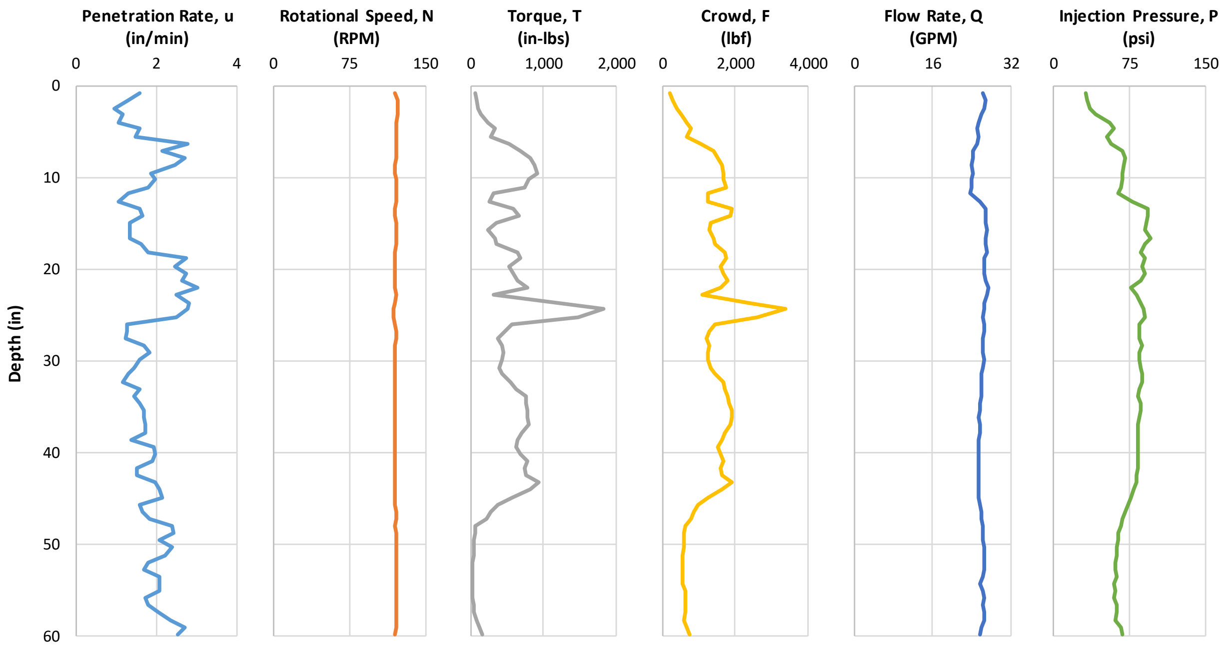

Figure 3-1. Example of the monitoring system graphical display submitted to the owner.

Table 3-1. Example of tabular data submitted to the owner.

Depth (in)	Pen. Rate, u (in/min)	Rot. Speed, N (RPM)	Torque, T (in-lb)	Crowd, F (lbf)	Flow Rate, Q (GPM)	Inj. Pressure, P (psi)
0.8	1.57	120	70	190	26.3	31.9
1.6	1.30	122	81	297	26.8	34.1
2.4	0.97	122	93	383	26.6	35.9
3.1	1.16	122	146	502	26.1	42.3
4.0	1.08	122	232	661	25.5	55.3
4.7	1.60	122	328	771	25.1	60.3
5.5	1.47	122	274	685	25.4	52.7
6.2	2.78	121	530	1,050	25.0	57.1
7.1	2.14	121	677	1,383	24.4	68.8
7.9	2.70	121	813	1,519	24.2	70.9
8.6	2.45	120	885	1,649	24.0	70.0
9.5	1.88	120	910	1,692	24.2	68.1
10.2	1.96	121	793	1,670	23.9	68.3
11.0	1.81	121	735	1,735	24.1	66.8
11.8	1.29	121	320	1,232	23.7	64.5
12.6	1.05	121	257	1,265	25.7	77.7

3.3.2 Instrumentation

The following provides the recommended sensor type for each monitored drilling parameter:

- Hydraulic torque – pressure transducer
- Hydraulic crowd – pressure transducer
- Mechanical torque – strain gauge instrumentation (torque rosettes – full bridge)
- Mechanical crowd – strain gauge instrumentation (T-element gauges – full bridge)
- Penetration rate – wheel mounted rotary encoder, draw wire sensor, string potentiometer
- Rotational speed – proximity or hall effect sensor
- Flow rate – flow meter
- Fluid injection pressure – pressure transducer
- Fluid density – flow meter
- Fluid dynamic viscosity – flow meter
- Vibration – accelerometer
- Inclination – inclinometer
- Direction of rotation – rotary encoder

3.4 Drilling Instrumentation Calibration

The measuring equipment must be checked and/or calibrated regularly according to the manufacturer's specifications or by the governing body overseeing the MWD investigation. A calibration report should be generated, and a copy of the report should be kept with the drill rig maintenance log. A copy of the latest calibration report must be available at the job site and should be kept with the drill rig operator's manual. Calibration of the sensors and recording system must be performed at the following intervals:

- Before using new monitoring equipment
- When changes to the previously calibrated drilling or monitoring equipment occur
- Before the start of each new project
- At least every six months during continuous active drilling
- When previously calibrated equipment is repaired
- Yearly, if certifications are made by the third-party control at regular intervals
- As determined by the governing body or owner

For drilled shafts and ACPs, calibration drilling should be completed on demonstration shafts/piles prior to drilling test piles and production piles to ensure the equipment is functioning properly and meets the requirements of the specified MWD Quality Class.

3.4.1 Mechanical Torque

Mechanical torque is measured by torque rosettes affixed to a small drill rod or coupler that remains at the top of the drill string or a coupler placed somewhere within the drive shaft. Couplers placed within the drive shaft must account for gear reductions. The torque rosettes must be setup in full bridge to compensate for thermal and bending effects. Mechanical torque is calibrated by testing the instrumented device in a controlled system. For smaller instrumented devices used for site investigation purposes, the instrumented device is leveled horizontally with one end fixed and the other free to twist with a moment arm of known length attached. Weights are added to the moment arm incrementally and loading is sustained until the signal received by the digital readout stabilizes. A calibration curve and equation are then developed to transform the digital or analog signals into physical measures of torque (ft-lb). Once the calibration curve is developed, predicted measurements from the device are then compared to the known torque values to determine the average error in measurements.

3.4.2 Mechanical Crowd

Mechanical crowd is measured by strain gauges affixed to a small drill rod or coupler that remains at the top of the drill string. The strain gauges must be setup in full bridge to compensate for thermal and bending effects. Mechanical crowd is calibrated by placing the instrumented device in a controlled system. For smaller instrumented devices used for site investigation purposes, the instrumented drill rod is loaded axially, with a calibrated load cell inline. Loading is applied incrementally and sustained until the signal received by the digital readout stabilizes. A calibration curve and equation are then developed to transform the digital or analog signals into physical measures of crowd (lbf). Once the calibration curve is developed, predicted measurements from the device are then compared to the known crowd values to determine the average error in measurements.

3.4.3 Rotational Speed

Rotational speed is measured by mechanically fastening a proximity sensor on the rotary table in a stationary position to detect rotary head bolts as they rotate. Once the sensor is in place, the number of bolts to be detected over a full rotation are programmed into the DAQ module. For calibration, the number of rotations per minute are counted multiple times at various rotational speeds and compared to the rotational speed readout. A calibrated tachometer can also be used for calibration.

3.4.3.1 Direction of Rotation

For certain drilled shaft excavations, drilling buckets may be used to increase the efficiency of drilled debris removal. Drilling bucket operations require reverse rotation to close off the base of the bucket. The reverse rotation should not be counted as drilling. Therefore, it is necessary to identify the direction of rotation via a wheel-mounted rotary encoder. Similar to the proximity sensor, the rotary encoder is also mechanically fastened to the rotary table in a stationary position in which the encoder wheel contacts the outer circumference of the rotating portion of the rotary head. The pulse signal sent to the DAQ module allows the direction of rotation to be determined directly.

3.4.4 Penetration Length and Rate

Penetration lengths are measured using a draw-wire rotary encoder (string potentiometer) or a wheel-mounted rotary encoder set to follow an external track mechanically fastened to the drill rig's mast. During advancement, the rotary encoder sends a pulse signal to the DAQ module. For calibration, a specified length of travel is measured physically, and the number of pulses recorded over the tracked length are then used to determine the number of pulses per unit length of travel. The DAQ module should track the time of travel automatically, which allows the penetration rate to be determined directly.

During drilling, the depth of the tool is determined relative to the ground level or another fixed referenced point. If drilling tools are changed, the change in tool length must be accounted for. This requires re-zeroing the depth sensor at the fixed refence point prior to resuming drilling. In general, this specification often only applies to drilled shafts where the tool continuously moves in and out of the hole and the tooling is more frequently changed based on the strata encountered and the drilling process.

3.4.5 Hydraulic Torque and Crowd

Hydraulic lines controlling torque and crowd must be tapped with individual pressure transducers. The pressure transducer can be tied into the hydraulic lines where existing sensors are located or in locations along the hydraulic lines where differential pressures are not experienced. Torque pressure is checked by rotating the drill string or Kelly system without penetration and crowd pressure is checked by moving the drill string or Kelly system up and down without rotation. This ensures the signals received are recorded by the appropriate port in the DAQ module. The pressure transducer's accuracy is checked using a hydraulic pump with a calibrated digital readout connected directly to the transducer. The hydraulic pressures are verified in small increments over the pressure transducer's full range.

3.4.5.1 Hydraulic Conversion

When drill rigs with hydraulically driven torque and(or) crowd systems are to be monitored, proper hydraulic conversions must be developed to transform the measured hydraulic pressures into physical measures of torque (ft-lb) and crowd (lbf). Hydraulic conversions must be developed for each individual drill rig monitored. Drill rig specifications must be obtained from the drill rig manufacturer based on the serial number affixed to the drill rig. Drill rig specifications obtained from an operator's manual are considered generic and not valid for MWD purposes under these specifications. In many cases drill rigs have custom features that may affect proper conversion if generic values are obtained from an operator's manual.

For accurate hydraulic conversion, the baseline pressure for torque (T_{BP}) and crowd (F_{BP}) must be accounted for which requires baseline measurements of the hydraulic pressures to be taken prior to the start of drilling each day and should be included in the field report. Baseline hydraulic pressures fluctuate based on the condition of the drill rig. A recently serviced drill rig will often produce lower baseline pressures than a drill rig that requires maintenance. Baseline pressures can be estimated by the rig manufacturer but must be measured on the drill rig after the rig is warmed up each day for accurate in situ assessment.

3.4.5.2 Hydraulic Torque Conversion

Most drill rigs provide multiple gears for various drilling modes and applications. A torque versus rotational speed (*T-N*) chart (**Figure 3-2**) must be obtained from the rig manufacturer or developed by an experienced MWD technician with sample calculations for converting hydraulic torque pressures (psi) to physical measures of torque (ft-lb or in-lb). Sample calculations must be provided for each gear used during drilling. Hydraulic pressures can fluctuate, and it is possible to exceed the *T-N* curve in practice. Therefore, the output torque value should be limited to the maximum torque value defined by the *T-N* curve for consistency.

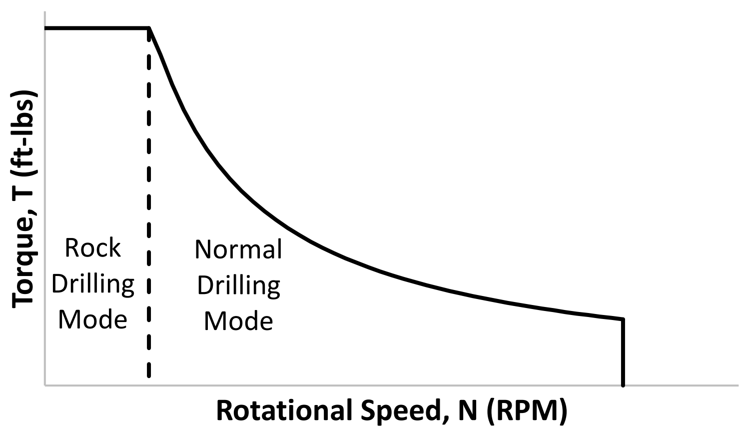

Figure 3-2. Torque vs. rotational speed chart indicating rock and normal drilling modes.

3.4.5.3 Hydraulic Crowd Conversion

For hydraulic crowd, a single hydraulic conversion coefficient (K_F) must be developed based on the drill rig capabilities and specifications and demonstrated through sample calculations.

3.4.6 Fluid Injection Flow Rate

Fluid injection flow rate is measured by a flow meter placed in-line with the existing fluid injection hoses. The flow meter should be placed directly downstream of the pump. For calibration, the time to fill a volumetric container with water is recorded multiple times and compared to the flow meter readout. The flow rate may also be verified by comparing the flow meter readout to that of a documented calibrated flow meter.

3.4.7 Fluid Injection Pressure

Fluid injection pressure is measured by a pressure transducer placed in-line with the fluid injection hoses. The pressure transducer should be placed directly downstream from the pump. The pressure transducer is calibrated using a hydraulic pump with a calibrated digital readout connected directly to the transducer. Hydraulic pressures are verified in small increments over the pressure transducer's full range.

3.5 MWD Data Processing

MWD data is often sampled per unit time which is referred to as time-referenced-data. For proper analyses, the collected data must be processed and organized in a columnar format with each drilling parameter measurement referenced to depth, which is referred to as depth-referenced-data. This is required because different rates of penetration are expected due to the various geomaterials or range of strengths that may be encountered throughout the drilling process. Consequently, changes in penetration rate inherently create differences in the penetration length achieved per unit time. In order to properly average drilling parameters over a specified recorded depth increment (e.g., volume excavated), equal individual lengths of measure must be used. Therefore, time-referenced-data must be transformed into depth-referenced-data of equal lengths before proper averaging can take place. Individual drilling parameters must be properly averaged per recorded depth increment (Section 3.6.1 and 3.6.2) prior to calculating compound parameters. Noncompliance will invalidate the MWD results.

Note: For AME systems that are only capable of producing time-referenced-data, the Florida Department of Transportation's ACP MWD analysis spreadsheet must be used to process the data in a depth-referenced-format.

3.6 MWD Quality Class

The MWD Quality Class specifies the required drilling parameters that must be measured and the depth increment in which the drilling parameters must be recorded. Under these specifications, manual recording of the drilling parameters is not considered valid. Therefore, the drilling parameters must be recorded automatically by a monitoring system. MWD Quality Classes are provided for site investigation MWD and bored piles (drilled shafts and ACPs) MWD, separately. This is because exploratory drilling conducted during a site investigation often requires fluid injection to remove the drilled debris, whereas drilled shaft and ACP drilling does not require fluid injection. Exploratory drilling using hollow stem augers may follow the MWD classification parameter requirements for drilled shafts and ACPs but must adhere to the sampling frequency requirements for exploratory drilling. All drilling parameter measurements must have an accuracy of 1% of the full measured range.

3.6.1 Site Investigation MWD

Table 3-2. MWD Quality Class for site investigation applications.

Quality Class	Number of Parameters	Required Measured Drilling Parameters	Recorded Depth Increment	Sampling Frequency
1	6 or more**	• Torque • Crowd • Penetration Rate • Rotational Speed • Injection Flow Rate • Injection Pressure	1-inch or less	100 Hz Minimum*
2	5	• Crowd • Penetration Rate • Rotational Speed • Injection Flow Rate • Injection Pressure	2-inches or less	10 Hz
3	3	• Crowd • Penetration Rate • Rotational Speed	4-inches or less	1 Hz

*The sampling requirements must be met. Failure to meet the sampling requirements will result in a lower class designation, regardless of the number of drilling parameters measured. **For Class 1 in situ soil identification and geo-mechanical assessment, vibration monitoring is recommended.

The following provides the intended evaluation type for each quality class:

- Class 1 – In situ rock strength assessment, in situ soil identification and geo-mechanical assessment, void detection, and thin layer changes
- Class 2 – Void detection and layer changes
- Class 3 – Layers changes

3.6.2 Drilled Shaft and ACP MWD

Table 3-3. MWD Quality Class for drilled shaft and ACP applications.

Quality Class	Number of Parameters	Required Measured Drilling Parameters	Recorded Depth Increment	Sampling Frequency
1	4 or more	• Torque • Crowd • Penetration Rate • Rotational Speed	1-inch or less	1 Hz Minimum
2	4	• Torque • Crowd • Penetration Rate • Rotational Speed	2-inch or less	
3	3	• Torque • Penetration Rate • Rotational Speed	4-inches or less	

The following provides the intended evaluation type for each quality class:

- Class 1 – In situ rock strength assessment, delineation between soil and rock, side shear shaft capacity estimation, and layer changes
- Class 2 – In situ rock strength assessment and layer changes
- Class 3 – Layer changes

3.6.3 Drilled Shaft and ACP MWD Monitoring Recommendations

- For all bored piles, vertical and battered, it is recommended to monitor inclination as an additional drilling parameter to ensure the foundation element does not deviate from the intended axis of loading.
- The rate of penetration should be controlled to provide at least one sampled measurement per recorded depth increment in accordance with the designated Quality Class. It is encouraged to provide multiple sampled measurements per recorded depth increment, which may require increasing the sampling frequency above the minimum requirement.
- For Class 1 delineation between soil and rock, vibration monitoring is recommended. This will require the sampling frequency to be increased to a minimum of 100 Hz for all drilling parameters.

3.7 Compound Drilling Parameters

Compound drilling parameters comprise a combination of individual drilling parameters that enhance the measurable drilling response due to changes in the strata encountered (**Table 3-3**). Compound parameters that focus on responsive drilling parameters provide a more accurate and reliable assessment of in situ geo-mechanical properties, especially in rock. For example, specific energy (Eq. 1; Teale 1965) has been shown to produce reliable correlations with conventional geo-mechanical properties. The equation separates the thrust and rotational components of rotary drilling and focuses on the torque-to-penetration rate (T/u) ratio in which both parameters are responsive. In controlled experiments, torque and penetration rate used in combination have provided reliable indications of changes in geo-mechanical strength properties. However, the T/u ratio must be normalized by the method-based and controlled drilling parameters, rotational speed, and bit diameter, for accurate in situ assessment. This is because variable rotational speeds and bit diameters will affect the torque requirement per penetration rate while drilling in a homogenous mass. Equation 1 developed by Teale (1965) provides proper normalization. Research has also shown that the rotary component of the specific energy equation provides a significant contribution to the total specific energy recorded; whereas the thrust component, comprised only of method-based and controlled drilling parameters, is often negligible.

Table 3-3. List of compound drilling parameters.

Equation No.	Compound Parameter	Equation	Reference
(1)	Specific Energy	$e = \frac{F}{A} + \frac{2\pi NT}{Au}$	Teale 1965
(2)	Drillability Strength	$D_s = \frac{64NT^2}{Fud^3}$	Karasawa et al. 2002
(3)	Penetration Resistance	$P_R = (t)_{z=1\,inch}$	ISO/IEC 2016
(4)	Somerton Index	$S_D = \frac{F}{A}\left(\frac{N}{u}\right)^{0.5}$	Somerton 1959
(5)	Soil-rock Resistance	$R_{SR} = \frac{F}{Au}$	ISO/IEC 2016
(6)	Alteration Index	$AI = 1 + \frac{F}{F_{max}} - \frac{u}{u_{max}}$	Pfister 1985
(7)	Hardness Parameter	$\Gamma_{hard} = \frac{NFd^2}{uT}$ $\Gamma_{easy} = -\frac{1}{\Gamma_{hard}}$	Bingham 1965
(8)	Exponent Method	$E = \frac{log\left(\frac{u}{Nd}\right)}{log\left(\frac{Fd}{T}\right)}$	Jordan & Shirley 1966

4. Test Procedure

4.1 General

The high resolution profiles of individual and compound drilling parameters obtained from MWD can be used to develop a near-continuous soil/rock profile and provide information including but not limited to: quantifying changes in subsurface conditions, assessing in situ geo-mechanical properties, identifying voids or faults, optimizing rock coring recoveries, ensuring the rock quality designation is reflective of the strata encountered, providing drilled shaft QA/QC by quantifying rock socket lengths, and optimizing drilling operations. MWD can be conducted in soil, intermediate geomaterial (IGM), and rock, either on land or over water.

For drilled shaft and ACP MWD applications, after the MWD test, the borehole will be used to construct a shaft, pile, or caisson that will be used to support structures. The MWD results can be used to ensure it meets design criteria via specific energy. In the case of load tested shafts or piles, project-specific correlations can be developed between the average specific energy recorded from MWD in the footprint of the load tested shaft/pile, and the load tested unit side shear measured in fully mobilized instrumented shaft/pile segments. The developed correlation can then be applied to subsequent production shafts or piles to provide QA/QC.

Note: In order to develop valid correlations, the shaft/pile segments considered must be fully mobilized.

4.2 Positioning the Drill Rig

Measuring While Drilling can be performed at each drilling location, therefore, it should be performed for each design boring and each production drilled shaft or ACP location for the foundation of the structure. The distance between each MWD test location should be sufficient to prevent interaction effects which will vary based on the MWD application. For site investigation MWD, the distance between each borehole must be 20 times the borehole diameter at minimum. Certain MWD applications may require larger spacing. Nearby excavations should also be avoided.

The drill rig must be positioned in a manner that allows the axis of crowd to be as close to vertical or the desired axis of inclination as possible. Deviation from the intended axis should be less than 2 degrees. The axis of the drilling tool or drill string must correspond to the loading axis at the start of penetration. It is critical to ensure axial alignment is properly adjusted prior to the start of each drilling pass because adjustments made during drilling often result in eccentric rotation, excessive vibration, and added drilling resistance, each of which may invalidate the MWD test results.

4.3 Drilling Guidelines and Procedures

Prior to collecting MWD data for geotechnical interpretation, drilling guidelines and procedures must be developed to ensure each drilling tool is used efficiently. Interdependent relationships exist between each of the drilling parameters and these relationships must be quantified to ensure a reliable MWD program is developed. This requires identifying an optimum interdependent range for each controlled drilling parameter, a target penetration rate, and torque and crowd limitations. The optimum ranges will be dependent upon the drilling application, type of drilled debris removal system, and the geometry of the drilling tool used. Developing drilling guidelines and procedures often requires calibration drilling in a homogenous medium (rock or soil) with specified laboratory tests conducted on samples collected in the footprint or in a nearby borehole for validation.

For drilled shaft and ACP applications, full scale instrumented load tests in which full mobilization is achieved can be used as replacement to laboratory tests conducted on collected samples. However, the raw data collected during the load test(s) must be obtained and the load test interpretation must be reviewed for accuracy by a qualified engineer responsible for the MWD tests.

Calibration drilling should be completed before using new drilling equipment or when changes to the previously calibrated drilling equipment occurs. Calibration drilling should also be conducted before the start of each new project and equipment calibration must take place prior to calibration drilling. The following should be conducted during calibration drilling to develop valid MWD guidelines and procedures:

- Check the drill rig to ensure it is in proper working condition and suitable to complete the intended drilling application. Worn rotary tables are especially problematic for exploratory drilling applications and often induce eccentric rotation with excessive vibration. In general, the drill rig and accompanying equipment should be operated well below their maximum capacity to assist in conducting a successful MWD investigation.

- If fluid injection is required to remove drilled debris from the borehole, select an appropriate drilling slurry based on historical data or relevant geological or hydrological data. Check the flushing channels of the drill bit and drill rods to ensure they are fully open and not clogged with drilled debris. Determine an appropriate range of flow rates to be used during drilling. The optimum flow rate range should be based on the suggested range of cuttings return specified in Section 2, although, some adjustments may be necessary depending on the drilling application and geomaterials to be encountered. If fluid injection is not required, proceed to the next step.

- Determine the optimum rotational speed range for the drilling tool. Recommendations are often provided by the drilling tool manufacturer but may need to be adjusted for the intended drilling application.

- Determine torque and crowd limitations that should not be exceeded during drilling. For exploratory drilling that requires fluid injection, the torque and crowd limitations will be dependent upon the flow rate. The flow rate must be sufficient to efficiently flush the drilled debris from the cutting face of the drill bit. Failure to efficiently flush the face of the bit will result in an accumulation of drilled debris with a subsequent increase in frictional resistance which will invalidate the MWD test.

  The torque and crowd limitations can be identified by slowly increasing crowd while drilling in a homogenous medium. Once the limitations have been reached, a rapid increase in torque and crowd will be experienced which indicates an overaccumulation of drilled debris at the cutting face and signifies the flow rate is no longer sufficient to efficiently flush the drilled debris at the current rate of drilling. This procedure should be repeated using various flow rates within the identified optimum range to develop a limiting torque per flow rate curve.

  During each subsequent MWD test, crowd must be regulated to ensure the torque limitation, based on the flow rate, is not exceeded.

  Note: For drilling applications that use fluid injection, crowd should not be used as the limiting parameter based on the flow rate. This is because crowd is affected by changes in injection pressure which can occur often during drilling. A change in injection pressure will inherently change the limited amount of crowd that can be applied based on the flow rate which will invalidate any previously developed crowd limitations. Torque is unaffected by changes in injection pressure and therefore the torque limitation based on the flow rate must be followed.

  For drilled shafts and ACPs, the crowd limitation is in place to avoid overturning the drill rig or damaging the Kelly system and the torque limitation is in place to reduce the number of breakdowns from overworking the system.

- Determine the optimum range of penetration per rotation (*u/N*) based on the geometry of the drilling tool. This is often an iterative process of adjusting various drilling parameters. The optimum range should be investigated while drilling in a homogenous medium. The optimum *u/N* range is then identified by the stabilization of specific energy (Eq. 1).

- Determine a target penetration rate based on the low-end threshold of the optimum *u/N* range and the rotational speed selected. The target penetration rate should be achieved or exceeded throughout the entirety of each MWD test.

Once the guidelines are established for a drilling tool, a drilling procedure is then developed to ensure the optimum ranges identified are maintained during subsequent drilling to validate each MWD test. The developed guidelines and procedures must be documented prior to the start of the MWD investigation. The drill rig, drilling tool configuration, and slurry type (if required) should remain unchanged throughout the MWD investigation. Changes to any one of these drilling variables must be noted and accounted for through additional calibration. Developed guidelines and optimum parameter ranges should not be used for other drilling tools. Drilling tools with unique geometries produce various degrees of mechanical efficiency when excavating geomaterial, and this results in a unique relationship between the drilling response and the geomaterials encountered. Consequently, the drilling guidelines and procedures developed for a specific drilling tool are not suitable for other drilling tools, regardless of the drilling application.

During the MWD test, any event that may affect the results of the parameter measurements must be reported. The drill rig operator should avoid adjusting the rotary table during drilling as this may induce eccentric rotation and excessive vibration that can lead to erroneous MWD results and damage to the equipment and drill rig. If a drilling tool is damaged, shows signs of significant wear, or is replaced for any reason, this information must be noted in the field report and accounted for or removed from the data interpretation. Drilling should be terminated if any of the following occurs:

- There is risk of injury
- The capacity, torque and/or crowd, of the drill rig is reached
- The established target penetration rate cannot be achieved
- The equipment may be damaged
- Continuous clogging causes large spikes in injection pressure that exceed the capacity of the fluid injection hoses
- Eccentric rotation becomes unmanageable or excessive vibration occurs

4.4 Factors Influencing MWD Results

4.4.1 Tool Influence

Different drilling tools produce various degrees of mechanical efficiency for excavating geomaterials, and this results in a unique relationship between the drilling response and the strata encountered. The mechanical efficiency is dependent upon the shape of the cutting face and the optimum rate of penetration per rotation which is dictated by the size of the cutting teeth relative to the cutting face. Therefore, the type of drilling tool must be recorded. Various drilling tools can be used at a site; however, each unique drilling tool must have its own drilling guidelines and procedures developed during calibration drilling to validate the MWD tests.

Bit wear can influence the mechanical efficiency of the drilling tool; therefore, it is critical to quantify the degree of bit wear before and after each MWD investigation or test, dependent upon the drilling application. Research has shown that significantly worn drilling tools can reduce the optimum penetration rate by a third and increase the specific energy by a factor of three which invalidates the MWD results. Drilling tools should be well maintained and replaced at appropriate intervals.

4.4.2 Drill Rig Influence

The characteristics of the drill rig (e.g., capabilities, hydraulic design, etc.) have an influence on the MWD results. Therefore, care should be taken when comparing MWD results obtained by different drill rigs at the same site. The characteristics and specifications from each drill rig used on a site shall be reported.

The drill rig's rotary system should be checked routinely to ensure concentric rotation of the drilling tool occurs. Worn rotary tables will induce eccentric rotation which leads to increased drilling resistance and excessive vibration downhole. For rock coring applications, this often leads to diminished core recoveries and an RQD assessment that does not reflect the in situ conditions. Furthermore, eccentric rotation and excessive vibration will invalidate the MWD test and may damage the drill rig or drilling equipment. It is recommended to incorporate a vibration sensor within the MWD system to quantify changes in vibration due to eccentric rotation while performing calibration drilling in a standardized homogenous medium.

4.4.3 Operator Influence

The drill rig operator should be familiar with MWD and should be instructed regarding the investigation guidelines and procedures in Section 4.3. The intention of establishing drilling procedures is to reduce any inefficient drilling practices, induced by the operator, that may affect the MWD test results and the resulting interpretation of these results. Following the established guidelines and procedures will ensure the MWD results are consistent when it is necessary to interpret a series of tests completed by one or more different drill rigs. A change in driller should be avoided if possible but if this is unavoidable, the change must be noted in the field report.

4.5 Test Completion

After the MWD test is complete, the penetration length achieved should be verified. For site investigation MWD, this often requires counting the drill rods as they are retrieved from the borehole and summing their total length with the drilling tool length and comparing the cumulative value to the penetration length recorded by the MWD system. For drilled shaft MWD, comparative measurements are made by a weighted tape placed down the excavated shaft, often conducted by the Construction Engineering Inspector (CEI). For ACPs, reference marks placed on the auger leads are counted during advancement and withdrawal.

Drilling equipment and tooling should be cleaned upon the completion of testing and should be well maintained. Drilling tools and drill rods should be inspected for clogging. If clogging or any excessive wear or damage is identified, it must be noted in the field report. Similarly, any drill rig operational irregularities or maintenance requirements observed should also be reported.

For Quality Class 1 MWD tests, the baseline readings of each monitored parameter recorded prior to the start of the test should be compared to the baseline readings recorded after the MWD test is completed. If the drift of any measured parameter is greater than the tolerance specified during equipment calibration, the results should be discounted, or the test should be designated with a lower class. Deviation outside of tolerance may indicate sensor malfunction or damage in which the sensor must be repaired or replaced prior to additional MWD tests.

In order to quantify the influence of tool wear on the measured drilling parameters, the condition of the initial and final wear of the tool should be checked and reported. Taking before and after pictures is often beneficial for this determination. Research has shown that tracking the total energy while drilling with the same tool may be an acceptable approach to track drill bit and rig wear. However, further investigation is encouraged before solely relying on this approach.

5. Reporting

The information specified in Section 5.1 through 5.5 should be reported in the field report, test report, or both as indicated. If the duration of the test is not available from the MWD system, the start and end times of the test should be reported. The test reports must include a copy of the MWD log and an electronic file of the recorded data in a standardized format. The graphical presentation of the test results must be uniform for a specific project and adhere to these requirements. Preliminary description of the soil and rock based on visual inspection should be reported (without correction deduced from MWD) on a summary log and included in the field report.

Table 5-1. MWD reporting requirements for general information.

5.1 General Information	**Field Report**	**Test Report**
Reference to this standard		X
Company executing the test	X	X
Name of the operator	X	X
Name and signature of MWD technician of record		X
GWT (if encountered) and date and time of recording	X	X
Depth of predrilling or excavation	X	X
Observations concerning the ground conditions	X	X
Observations concerning the condition of the drill rig and/or tools	X	X
Depth and possible causes of any stops in penetration	X	X
Stop criteria (e.g., target depth, max crowd achieved, inclination, etc.)	X	X

Table 5-2. MWD reporting requirements for the location of the test.

5.2 Location of the Test	**Field Report**	**Test Report**
Test identification	X	X
Top elevation of the borehole or excavated shaft	X	X
Local and general coordinates (preferably GPS coordinates)		X

Table 5-3. MWD reporting requirements for the test equipment.

5.3 Test Equipment	Field Report	Test Report
Drilling tool type	X	X
Geometry, dimensions, and characteristics of the tools used	X	X
Type of drill rig used	X	X
Drill rig specifications		X
Type of MWD data acquisition system used	X	X
Serial number of the data acquisition system used		X
Measuring ranges of the sensors used		X
Calibration records for each of the sensors		X

Table 5-4. MWD reporting requirements for the test procedure.

5.4 Test Procedure	Field Report	Test Report
Quality Class	X	X
Drilling guidelines and procedures developed during calibration		X
Date of test	X	X
Starting time of test (if relevant)	X	X
Depth of the start of penetration	X	X
Type of drilling fluid (if required)	X	X
Tool wear before test (visual and/or total specific energy)	X	X
Tool wear after test (visual and/or total specific energy)	X	X

Table 5-5. MWD reporting requirements for the measured parameters.

5.5 Measured Parameters	Field Report	Test Report
Baseline readings of drilling parameters before and after the test	X	X
Drilling parameter readings according to Quality Class	X	X
Duration of test	X	X
Corrections applied during data processing		X

6. Terms and Definitions

Borehole – A hole bored into the ground for evaluation in support of geotechnical exploration, characterization, and design.

Compound drilling parameters – A combination of individual drilling parameters that enhance the measurable drilling response due to changes in the strata encountered.

Crowd (downward thrust) – Downward axial force applied to the drilling tool.

Data acquisition (DAQ) module – A module that samples signals acquired from measuring real world physical conditions and converts the resulting samples into digital numeric values that can be processed by a computer.

Drilling parameters – Parameters measured and recorded on the drill rig during the drilling process (e.g., torque, rotational speed, penetration rate, etc.).

Flow meter – An instrument used to measure the mass or volume of a liquid or gas per unit time.

Fluid injection flow rate – Volumetric flow rate of circulating drilling fluid (i.e., slurry).

Fluid injection pressure – Surface pump pressure required to remove drilled debris from the borehole.

Holdback pressure – The hydraulic pressure limiting the penetration rate.

Inclination – The angle of deviation from a vertical borehole.

Junction box – An enclosure that protects a connection of wires carrying electrical current.

Penetration length – The change in depth during a specified interval of drilling measured along the axis of the borehole. The penetration length is often recorded from the ground surface elevation (GSE) or a referenced elevation atop the borehole or shaft.

Penetration rate – The change in drilling depth per unit time as the drilling tool is advanced into the ground.

Pressure transducer – A transducer that converts pressure into an analog electrical signal.

Proximity (Hall effect) sensor – A sensor that emits an electromagnetic (EM) field and detects changes in the EM field caused by the presence of nearby objects without physical contact.

Recorded depth increment – The maximum distance between the depths of consecutive recorded drilling parameters. Time-based sampled measurements are averaged over the recorded depth increment.

Rotary encoder – An electro-mechanical device that converts the angular position or motion of a shaft or axle to analog or digital output signals.

Rotational speed – Drilling tool revolutions per unit time.

Torque – Rotational torque applied to the drilling tool.

Vibration – Acceleration due to reflected energy generated at the drill bit interface or within the drill string.

7. Symbols

Symbol	Name	Unit
T	Torque	in-lbs
F	Crowd or downward thrust	lbf
u	Penetration rate	in/min
N	Rotational speed	RPM
Q	Fluid injection volumetric flow rate	GPM
Q_M	Fluid injection mass flow rate	lbf/min
P	Fluid injection pressure	psi
ρ	Injected fluid density	slugs/ft^3
μ	Injected fluid dynamic viscosity	lbf-s/ft^2
G	Vibration	ft/s^2
I	Inclination	degrees
l	Penetration length	in
t	Measured time	s, min
z	Measured depth	in, ft
Δz	Recorded depth increment	in, ft
d	Drill bit diameter	in
A	Cross-sectional area of excavation	in^2
T_{max}	Maximum Torque available on the drill rig	ft-lbs
F_{max}	Maximum crowd available on the drill rig	lbf
T_{BP}	Baseline torque pressure	psi
F_{BP}	Baseline crowd pressure	psi
K_F	Crowd conversion coefficient	lbf/psi
OP_{max}	Maximum operating pressure of drill rig hydraulic system	psi
T_P	Hydraulic torque operating pressure	psi
F_P	Hydraulic crowd operating pressure	psi
δ_{max}	Maximum hydraulic motor displacement	in^3/rev
δ_{min}	Minimum hydraulic motor displacement	in^3/rev
Q_H	Hydraulic fluid flow rate	in^3/min
X	Number of hydraulic motors	-
R_n	Gearcase reduction for each gear (n)	-
SPC	Stones per carat rating for diamond core bits	-
HQ	Core bit designation for a 2.5” core diameter	-
NQ	Core bit designation for a 1.9” core diameter	-
e	Specific energy	psi
D_s	Drillability strength	psi
S_D	Somerton index	-
P_R	Penetration resistance	min/1-in
R_{SR}	Soil-rock resistance	pci-min
GWT	Ground Water Table	ft
W_R	Weight of drill rod or drill string	lbf
q_u	Unconfined compressive strength	psi
q_{st}	Split tension strength	psi
q_{dt}	Direct tension strength	psi
S_u	Undrained shear strength	psi
f_s	Side shear strength	psi

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