Field Device to Measure Viscosity, Density, and Other Slurry Properties in Drilled Shafts

GRIP 2016
Presented by: Gray Mullins, Ph.D., P. E.
Problem Statement

- Drilled excavation requires slurry that falls within a set of parameters regarding density, viscosity, pH and sand content; typically, each slurry property is tested using a unique, separate test method.
- Slurry properties are measured every 2 hours for the first 8 hours and 4 hours thereafter.
- A downhole device to measure all properties real time may improve data quality and expedite construction.
- Establish method to automate each test
### FDOT Standard Specifications for Road and Bridge Construction
Section 455-15.8

#### Mineral slurries

<table>
<thead>
<tr>
<th>Item to be measured</th>
<th>Range of Results at 68°F</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>64 to 73 lb/ft³ (in fresh water environment) 66 to 75 lb/ft³ (in salt water environment)</td>
<td>Mud density balance: FM 8-RP13B-1</td>
</tr>
<tr>
<td>Viscosity</td>
<td>30 to 50 seconds</td>
<td>Marsh Cone Method: FM 8-RP13B-2</td>
</tr>
<tr>
<td>pH</td>
<td>8 to 11</td>
<td>Electric pH meter or pH indicator paper strips: FM 8-RP13B-4</td>
</tr>
<tr>
<td>Sand Content</td>
<td>4% or less</td>
<td>FM 8-RP13B-3</td>
</tr>
</tbody>
</table>

#### Polymer slurries

<table>
<thead>
<tr>
<th>Item to be measured</th>
<th>Range of Results at 68°F</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Polymer Slurry Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>62 to 64 lb/ft³ (fresh water) 64 to 66 lb/ft³ (salt water)</td>
<td>Mud density balance: FM 8-RP13B-1</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Range Published By The Manufacturer for Materials Excavated</td>
<td>Marsh Cone Method: FM 8-RP13B-2 Electric pH meter or pH indicator paper strips: FM 8-RP13B-4</td>
</tr>
<tr>
<td>pH</td>
<td>Range Published By The Manufacturer for Materials Excavated</td>
<td></td>
</tr>
<tr>
<td>Sand Content</td>
<td>0.5% or less</td>
<td>FM 8-RP13B-3</td>
</tr>
</tbody>
</table>
Existing Method to Measure Density

Standard mud balance
How to Automate Density Measurements

- **Hydrostatic Pressure Differential**
  - By comparing pressure data from two points with a known elevation difference, density can be calculated using:

  \[
  \rho = \frac{\Delta P}{g(h_2 - h_1)}
  \]

- **Archimedes Principle**
  - By monitoring the buoyant force created by a “float” of known volume, the density of the surrounding fluid may be calculated using the following equation:

  \[
  F_{buoyancy} = \rho_{\text{fluid}} \times V_{\text{displaced}}
  \]
Viscosity
Viscometer Measurements

Newtonian fluids
-Viscosity

Shear-thinning fluids
-Apparent viscosity
-Gel strength
-Yield point
Viscosity
Marsh Funnel Measurements

- Time (sec) required for 1qt of fluid to flow from standardized 3/16in orifice of a funnel.

- Pressure ranges from 0.8 - 0.5psi

- Flow ranges from 0.6 - 0.2gpm (26 to 75 sec)
How to Automate Viscosity Measurements

• Different viscosity slurries have unique flow vs pressure curves
• For the same flow rate, a more viscous material causes higher pressure to be developed.
Sand Content

Fixed volume of slurry is sieved wet washed through 200 sieve.

NOTE: Volumetric Sand Content

Indirect measure of suspended solids
How to Automate Sand Content Measurements

- If the viscosity of a pure bentonite slurry is known, a corresponding density can be expected.

- Any density increase above pure bentonite can be attributed to the suspended solids.

- Sand content is a portion of suspended solids.
Clean Slurry Density

![Graph showing the relationship between density and viscosity for different slurry types.](Image)

- **Super Gel X**
- **Pure Gold**
- **Florigel High Yield**
- **CETCO Polymer**
- **Wyo-Ben Natural**
- **Premium Gel**
- **Wyo-Ben High Yield**
- **Pure Gold 2016**
- **Pure Gold 2014**

Density (pcf) vs. Viscosity (sec/qt)
Sand content from density and viscosity
Approach

- Proof of concept
- Component Development
- System Fabrication
- Lab and Field Testing
Slurry Column Tests (Falling Head)
Slurry Column Tests

- Bentonite slurry viscosity
  - ranged from 26 (water) to 90 sec/qt
- Flow rates (12ft falling head)
  - 0 to 2 gpm
- Density
  - 64 to 71 pcf
- Sand contents
  - 0.25 to 10% by volume
Slurry Column (falling head)

Pressure (psi)

Flow (gpm)

3/16" ID Orifice

90 Sec

26 Sec Water

Water 32s 45s 62s 91s
40 Second Marsh Funnel

Influence of Sand on Flow vs Pressure Curve
## Test Batch Summary

<table>
<thead>
<tr>
<th>Batch</th>
<th>Average Marsh Funnel Test (sec)</th>
<th>Average Sand Content (%)</th>
<th>Density (lb/ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Sand</td>
<td>40.03</td>
<td>.25</td>
<td>64.81</td>
</tr>
<tr>
<td>Sand</td>
<td>39.3</td>
<td>6.58</td>
<td>68.24</td>
</tr>
</tbody>
</table>

Use density measurements to determine gravimetric sand content
Pressurized Flow Tests

Flow Meter

Pressure Transducer

Nozzle
High Flow Nozzles
High Flow / Pressurized

- Bentonite slurry viscosity
  - ranged from 30 to 140 sec/qt
- Flow rates (pumped)
  - 0 to 23 gpm
- Density
  - 64 to 66 pcf
- Sand contents
  - 0.25% pure bentonite only
High Flow (pump system)

3/8” ID Nozzle

- 143s
- 59s
- 46s
- 40s
- 31s
High and Low Flow
Select System Orifice

- Small orifice is affected most by changes in viscosity
- Large orifice less affected by debris
- Selection of system orifice based on balancing positive benefits
- Need largest possible pressure difference relative to transducer sensitivity
Low Flow Nozzles
Optimum Nozzle Selection

![Graph showing the relationship between pressure difference (psi) and length of orifice (in.) for different nozzle diameters (0.3" ID, 0.28" ID, 0.25" ID, 0.18" ID).]
System Concepts GRIP 2015

- Downhole self contained “dive bell”
  - Pressure
  - Flow
  - Density
  - Depth measured topside
System Concepts (GRIP 2015)

- All topside measurements
  - Pickup hose
  - Measure hose depth
  - Track flow from a given depth through the topside systems.
  - Correlate sample to measurements based on hose position and time in hose/flow.
Downhole Component Selection Considerations

- Pressure transducer(s)
  - Differential vs absolute
- Flow meter
  - Magnetic flux, Doppler, paddle wheel, ultra sonic
- Pump type and size
  - Centrifugal, diaphragm, peristaltic, Archimedes screw, piston pump
- Component power requirements
  - AC, DC, hydraulic, pneumatic
- Power source (top side power vs on-board batteries)
Downhole Component Selection Considerations

- Pressure transducer(s)
  - Differential
- Flow meter
  - Magnetic flux
- Pump type and size
  - Centrifugal with variable flow
- Component power requirements
  - DC (24-32, 10-15, 12 or 24VDC)
- Power source (2 On-board batteries; 12 or 24)
Power Requirements

- Onboard batteries 12 VDC
- 5 amps require large, heavy wire to combat voltage drop over a 100ft distance of cable.
- Component input requirements do not fall within the same range.
  - 12 VDC for pump
  - 10-15 VDC for flow meter
  - 24-32 VDC for both pressure transducers

<table>
<thead>
<tr>
<th>Description</th>
<th>Power Requirement</th>
<th>Req'd No. Cable / Tether Conductors</th>
<th>Output Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>12 or 24VDC</td>
<td>None for operation</td>
<td>N/A</td>
</tr>
<tr>
<td>Pump relay</td>
<td>12VDC triggered by computer system</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>Flow meter</td>
<td>10-15VDC</td>
<td>2 or 4 (for both output)</td>
<td>4-20mA current or digital counts</td>
</tr>
<tr>
<td>Nozzle pressure</td>
<td>24-32VDC</td>
<td>2</td>
<td>0-5VDC</td>
</tr>
<tr>
<td>Density pressure</td>
<td>24-32VDC</td>
<td>2</td>
<td>0-5VDC</td>
</tr>
<tr>
<td>Battery Charge</td>
<td>12 or 24VDC top to bottom feed</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>Battery Monitor</td>
<td>N/A</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>Pump Speed Control</td>
<td>N/A</td>
<td>3</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Power Requirements (continued)

- Boost Converter

- Input Voltage (3 to 35 V<sub>DC</sub>)
  - 12.8 V (battery)

- Output Voltage (3.5 to 35 V<sub>DC</sub>)
  - 30.4 V (chosen)
Concept Device

- Discharge nozzle
- Differential Pressure Reference Ports
- Two differential transducers
- Mag flux flow meter
- Variable flow pump
- Two 12V 5.5amp-hr batteries (optional 12 or 24V configuration)
- Pump pickup screen
Differential Pressure Transducer (density)

Sensor Body

30in

Pressure Transmitter Line

Sensor Membrane

Rubber Pressure Transmitter

Pressure Transmitter Line

Rubber Pressure Transmitter

SLURRY
Computerized DAQ System (CDS)

Connections
- Case charger
- USB DAQ / CPU
- DHU connector
- Depth encoder
- Pump control
- DHU relay/power
- DHU charger

Laptop Power Port
USB Connector
DHU Connector
Depth Encoder Input
Pump Controller
DHU Power Switch
DHU Charging Port
## Computerized DAQ System (CDS)

<table>
<thead>
<tr>
<th>Component</th>
<th>Sensor</th>
<th>Harness</th>
<th>DAQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density PT</td>
<td>White</td>
<td>Orange</td>
<td>2L</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>Red</td>
<td>2H</td>
</tr>
<tr>
<td>Flow PT</td>
<td>White</td>
<td>Pink</td>
<td>3L</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>Purple</td>
<td>3H</td>
</tr>
<tr>
<td>Flow Meter</td>
<td>White</td>
<td>Green</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>Gray</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Brown</td>
<td>Yellow</td>
<td>5L</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>Brown</td>
<td>5H</td>
</tr>
<tr>
<td>Pump Controller</td>
<td>Yellow</td>
<td>Blue</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>Bl-Gray</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>Bl-Green</td>
<td>N/A</td>
</tr>
<tr>
<td>Hot Line</td>
<td>Red</td>
<td>Bl-Brown</td>
<td>4H</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>Bl-Yellow</td>
<td>4L</td>
</tr>
<tr>
<td>Monitor</td>
<td>Red</td>
<td>Bl-Blue</td>
<td>1H</td>
</tr>
<tr>
<td>Relay</td>
<td>Red</td>
<td>White</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Black</td>
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<td>N/A</td>
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## Down Hole Unit (DHU)

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<tr>
<td>Flow Meter</td>
<td>White</td>
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<td>N/A</td>
</tr>
</tbody>
</table>
Transmitter / diaphragm purging
Assembly
Assembly
Calibrating Viscosity Measurements

- Very repeatable
- Actually two overlapping test curves at each viscosity
- 2nd order polynomial fit
- Slice this graph vertically at tenth points
Calibrating Viscosity Measurements

- Constant flow rate curves
Calibrating Viscosity Measurements

- Constant flow rate curves
- Natural logarithm fit

\[ y = 2.1619 \ln(x) - 5.3863 \quad R^2 = 0.9973 \]
\[ y = 1.9457 \ln(x) - 5.1771 \quad R^2 = 0.9988 \]
\[ y = 1.6979 \ln(x) - 4.7794 \quad R^2 = 0.9990 \]
\[ y = 1.4185 \ln(x) - 4.1933 \quad R^2 = 0.9988 \]
\[ y = 1.1076 \ln(x) - 3.4187 \quad R^2 = 0.9981 \]
Calibrating Viscosity Measurements

- Plot of coefficients and constants of trend lines

Equations from previous slide

\[ y = 2.1619 \ln(x) - 5.3863 \]
\[ R^2 = 0.9973 \]

\[ y = 1.9457 \ln(x) - 5.1771 \]
\[ R^2 = 0.9988 \]

\[ y = 1.6979 \ln(x) - 4.7794 \]
\[ R^2 = 0.999 \]

\[ y = 1.4185 \ln(x) - 4.1933 \]
\[ R^2 = 0.9983 \]

\[ y = 1.1076 \ln(x) - 3.4187 \]
\[ R^2 = 0.9981 \]
Calibrating Viscosity Measurements

\[ P = 1.4185 \ln(V) - 4.1933 \]

- \( P = \text{coefficient} \times \ln(\text{viscosity}) + \text{constant} \)
- \( \ln(\text{viscosity}) = \frac{\text{pressure} - \text{constant}}{\text{coefficient}} \)
- \( \text{viscosity} = e^{\frac{\text{pressure} - \text{constant}}{\text{coefficient}}} \)
Calibrating Viscosity Measurements

Example for 0.32 gpm:

Coefficient:  
= \(-1.5786x^2 + 3.8987x + 0.391\)  
= 1.477

Constant:  
= \(9.4229x^2 - 12.457x - 1.3042\)  
= - 4.326

\[P = 1.477 \ln V - 4.326\]

\[\text{viscosity} = e^{\left(\frac{P - (-4.326)}{1.477}\right)}\]

Given a measured pressure of 1.7 psi:

\[\text{viscosity} = 59.1 \text{ s}\]
Calibrating Viscosity Measurements

Calibration test shows predicted viscosity curve throughout flow range
Field Testing – Shaft Simulator
System Check (water)
Test Procedure

- Nozzle pressure required depth corrected offset
Field Testing – Procedure

1. Take baseline density pressure before introduction
2. Introduce device into hole, lower to first depth
3. Take baseline viscosity pressure at zero flow rate
4. Increase flow rate to desired test range, wait for stabilization (e.g. 0.25-0.35 gpm)
5. Take pressure and flow rate data until average is stable (10 sec)
6. Reduce flow rate to zero and move on to next depth
7. Repeat steps 3-6 at subsequent depths
Field Testing – Shaft Simulator

Density (pcf)

Sand Content (%)

Viscosity(sec)
Differential Pressure Transducer (density)

- Rubber Pressure Transmitter
- Pressure Transmitter Line
- Sensor Body
- Sensor Membrane
- Trapped air
- Pressure Transmitter Line
- Rubber Pressure Transmitter

Diagram showing the components of a differential pressure transducer.
Field Testing – Sarasota
Field Testing – Sarasota

- **Density (pcf)** vs. Depth (ft)
- **Sand Content (%)** vs. Depth (ft)
- **Viscosity (sec/qt)** vs. Depth (ft)
Field Testing – Ft. Myers
Second Generation

- Smaller unit
- Displaced volume / load cell
- Same pump, flow and nozzle pressure
Redesigned DHU (in water)
Conclusions / Lessons Learned

- Viscosity measurement system very stable.
- Density from differential hydrostatic pressure not a trivial pursuit.
  - Any bubbles will delay and skew pressure readings
  - Different length capillary tubes will cause temperature related drift in readings.
  - Transmitter to sensor elevations must be same on both sides of sensor.
- Displaced volume system shows promise
- Gravimetric suspended solids may be better measure of “sand content”
  - Poorly graded vs well graded suspended can have significant difference on actual “sand content”
  - Silt content, presently unmeasured, is detected with new system.
- Experimental prototypes were fast and easy to use.
Questions?