SLIDES: Directional Drilling: The Promise and the Peril

Alfred W. Eustes III

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Directional Drilling
The Promise and the Peril

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Directional Drilling

• The art and science of drilling a wellbore along a *predetermined* trajectory.

• The tools and techniques used are determined by the complexity of the well path and the desired precision of the attempt to follow that trajectory.
Relief wells
Controlling vertical wells
Inaccessible locations
Fault drilling
Re-entry/Multi-lateral wells
Reentering Existing Wells

Medium radius requires completion in shale

Original well

7- or 5-in. line

Short radius drains 6\(\frac{1}{4}\) in. – 4\(\frac{1}{4}\) in.
**New: Greatest Deviation.** Smedvig’s semisubmersible West Vanguard has set a new world record for deviated drilling. In Norsk Hydro’s gas injection well No. 6407/7-A-8H out on the Njord field, the West Vanguard crew achieved a deviation of 139° from vertical for the 9½-in. hole, using a conventional drill string with a Lyng LA 250BZ PDC drill bit and a 6¾-in. Mach 1 XL motor with a 9½-in. SOS bearing housing stabilizer. The well was drilled to a vertical depth of 8,999 ft (2,742 m) with a TD of 11,893 ft (3,625 m) in 1,083-ft (330-m) water depths. An average of 3.8° per 30 m DLS was required throughout the run, and this was achieved without oriented drilling.
Reference Systems and Coordinates

• **Depth Reference**
  - True Vertical Depth (TVD)
    • Pressure calculations
  - Measured Depth (MD)
    • Volume calculations
    • Geolograph

• **Reference Points**
  - Ground level (GL)
  - Rotary kelly bushing (RKB)
  - Rotary table (RT)
  - Rig floor (RF)
**Inclination**

- **Inclination (Drift)**
  
  - The angle (in degrees) between the local vertical (local gravity vector as indicated by a plumb bob) and the tangent to the well bore axis at a particular point.
  
  - By oilfield convention, $0^\circ$ is vertical and $90^\circ$ is horizontal.
Azimuth

- **Azimuth (hole direction)**
  - The azimuth of a borehole at a point is the direction of the borehole on the horizontal plane, measured as a clockwise angle (0° - 360°) from the North reference.
  - All magnetic tools give readings referenced to magnetic north; however, the final calculated coordinates are referenced to either true north or grid north.
Target

Driller: relative to borehole direction
Geological: relative to geology

Bigger is easier to hit
Radius Definitions

Long Radius
- 2° - 6°/100 ft
- 3000 - 1000 ft radii
- 6° - 40°/100 ft
- 1000 - 140 ft radii
- 2° - 6°/100 ft
- 1500 - 4000 ft radii
- 6° - 40°/100 ft
- 2000 - 6000 ft radii

Medium Radius
- 40 - 70°/100 ft
- 140 - 82 ft radii
- 300 - 3000 ft
- 1500 - 4000 ft

Intermediate Radius (Flex Motors)
- 70 - 150°/100 ft
- 82 - 40 ft radii
- 300 - 1000 ft

Short Radius (Articulated Motors)
- 70 - 150°/100 ft
- 82 - 40 ft radii
- 300 - 1000 ft
Build and Hold (Slant)

Kick off Point (KOP)
Build Section
Top of Slant
Slant
Target
“S” Type Well (Build and Drop)

- Kick off Point (KOP)
- Build Section
- Top of Slant
- Slant (Tangent)
- Slant Angle
- Top of Drop
- Drop Section
- Target
- Hang
Horizontal (Single)

Kick off Point (KOP)

Build Section

Target

Reach
Wall Force

- Force of tool joint against borehole wall
- According to A. Lubinski,
  - Keep WF less than 2,000 lbf in water based muds
  - Keep WF less than 3,000 lbf in non-aqueous based muds
- Problems from wall contact
  - Casing wear
  - Drill pipe wear
  - Fatigue failure
  - Keyseating

\[ WF = 2T \sin \left( DLS \frac{L_j}{2} \right) \]

\[ L_j = \text{length of joint} \]
Survey Techniques

- Find inclination and azimuth at various points along the wellbore
- Usually get
  - Inclination (from vertical)
  - Azimuth (from north)
  - Measured depth (from RKB, GL, etc.)
Surveying Data Gathering Techniques

- Simple drift
- Photographic film
  - disks / strip
- Memory modules
  - multi-shot / MWD
- Wireline
  - surface readout
- Mud pulse telemetry
  - MWD
Simple Drift

• Every rig has a simple drift
• Only measures inclination
  – No azimuth information
• Sometimes dropped right before a trip
• Sometimes run on slick line
• Operates on a pendulum
  – Timer
  – Punches paper disk (twice at 180° separation)
Magnetic Single-Shot

• Function
  - Provides photographic record of inclination, direction and toolface orientation at a single point in the open hole section of the well

• Limitations
  - Requires non-magnetic drill collars
  - Temperature
  - Must re-run to confirm changes in toolface
Electronic Multi-Shot

• Function
  - Records inclination, direction and toolface
  - Records raw magnetic and gravity field data
  - All data electronically measured and recorded

• Limitations
  - Needs non-magnetic drill collars
  - Temperature
MWD/LWD Measurements

- Inclination aka: drift, slant, angle
- Azimuth aka: direction, compass heading
  - Gravitational and magnetic field sensitivity
  - Magnetic dip angle
- Drilling operating parameters
  - Torque
  - Weight on Bit (WOB)
  - Pressure
- Tool face orientation (which way is the bit pointed)
- Sensor temperature
- Formation evaluation measurements
  - Gamma Ray, resistivity, density, neutron, sonic, pressure
Geosteering

• A technique used to direct a wellbore path
  - in terms of geologic features
  - not in terms of simple geometric constraints

• Requires close cooperation of geologist and drilling engineer

• Use of LWD and MWD helps determine a path through a formation while drilling

• To apply, need to have:
  - Knowledge of log response of formation(s)
  - Experienced personnel
  - Good MWD and LWD equipment

• Useful in
  - Reservoirs that are thin and/or complex
  - Medium to short radius horizontal wells
Survey Errors

- **Two types**
  - Systemic – regularly occurring and are not compensating
  - Random – irregularly occurring

- **Reading errors**
- **Mechanical malfunctions**
- **Calibration errors**
- **Instrument alignment**
- **Drillstring measurement**
- **Inherent math approximations**
- **Natural magnetic interference**
- **Hot spots**
- **Numerical calculations and data recording**
- **Gyroscopes**
  - Drift
  - Precession
  - Orientation
Station Errors

Probability distributions

Measured Depth

Horizontal View

Section View

2-sigma ellipsoid
Target vs Ellipse of Uncertainty

Target

Ellipse of Uncertainty

Wellbore Trajectory
Continuous Inclination & Azimuth

**Stationary Inclination**
- Accuracy: 0.1° at 1σ
- Resolution: 0.025°

**Stationary Azimuth**
- Accuracy: 1° at 1σ
- Resolution: 0.18°

**Tool face**
- Resolution: 6°

<table>
<thead>
<tr>
<th>Continuous inclination</th>
<th>Continuous azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>accuracy: 0.2°</td>
<td>accuracy: 2°</td>
</tr>
<tr>
<td>resolution: 0.03°</td>
<td>resolution: 0.5°</td>
</tr>
</tbody>
</table>

Survey stations inclination
Continuous inclination
Gravity tool face
Hole Depth (ft)

Inclination

Continuous inclination
Spider Plot (Platform Hogan)

About 5,000’
Anti-collision

• Major versus minor risk
  – Major – significant risk to people and environment
  – Minor – negligible risk
• Wellbore may have multiple risks
• Separation based on company rules (10 m)
• Anti-collision diagram
  – Traveling cylinder plot with tolerance lines
  – Preplanned trajectory
• Used in the field
  – Don’t cross the tolerance line
Positive Displacement Motor

- Drive Sub (Bit Box)
- Bearing Assembly
- Deflection Device
- Stator
- 1 Stage
- a) Mono Lobe
- b) Multi Lobe
- Universal Joint Assembly
- Rotor
PDM - Fluid Flow Path

Direction Of Rotation

Stator (Elastomer)

Rotor

Fluid Flow

Universal Joint
Short Radius: Drilling the Curve

**Flexible Fixed Bend Motor**

**Articulated Motor**
Rotary Steerable Systems

Direct Side Force
i.e. Push the Bit

Bit Tilt without Side Force
i.e. Point the Bit
Whipstock
# Technology Overview

## Build Rate (deg. 100’, deg/ 30m)

<table>
<thead>
<tr>
<th>Curvature</th>
<th>Long</th>
<th>Medium</th>
<th>Intermediate</th>
<th>Short</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Type</td>
<td>M1XL Motors</td>
<td>M1X Motors</td>
<td>M1XL Motors</td>
<td>Articulated Motors</td>
</tr>
<tr>
<td>MWD Type</td>
<td>Collar</td>
<td>Probe</td>
<td>Flexible (Primary Application)</td>
<td>Composites</td>
</tr>
<tr>
<td>Pipe Rotation</td>
<td>Conventional</td>
<td>Premium - Limited Rotation</td>
<td>Slide Drill - No Rotation</td>
<td>Special</td>
</tr>
<tr>
<td>Completions</td>
<td>Conventional - No Restrictions</td>
<td>Project Specific</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radius (ft.)</th>
<th>1000</th>
<th>140</th>
<th>80</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (m)</td>
<td>300</td>
<td>43</td>
<td>25</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost</th>
<th>$</th>
<th>$$$</th>
</tr>
</thead>
</table>

Side Force and Tilt Angle

- Hole Gauge
- Side Force at Bit
- Resultant Force at Bit
- Hole Axis
- Side Force at Stabilizer
- Formation Anisotropy
- Bit Tilt Angle
Dip Angle and Deviation Force

Hole Inclination = 30°
Real Dip Angle = 35°
Effective Dip Angle = 30° + 35° = 65°
There will be a **down-dip** deviation force

Hole Inclination = 0°
Real Dip Angle = 35°
Effective Dip Angle = 35°
There will be a up-dip deviation force

Hole Inclination = 35°
Real Dip Angle = 35°
Effective Dip Angle = 0°
There will be no deviation force

Asymmetric rock failure still deviates borehole.
Oriented Mode (Slide)

- **Wellbore Trajectory**
  - Controlled curvature
  - Controlled direction
  - No drill string rotation
Rotary Mode

- **Wellpath**
  - Behavior same as a rotary drilling assembly
  - Hole slightly over size
Influences on Direction

(a) (c) (b) (d)

Stabilizer
Torque and Drag

• Higher with
  - Any directional change
  - Undulations (mini-doglegs)
  - Thick mud cake
  - Ledges
  - Non-lubricating mud
  - Cuttings beds
  - Swelling formations

• Affects
  - Available WOB
  - Available TOB
  - Margin of overpull

• Changes with
  - Running in the hole
  - Pulling out of the hole
  - Sliding
    • Axial drag
    • Lock up
  - Rotation
Torque and Drag Example
Buckling

- Load starts bending the pipe
- When load reaches critical point, buckling starts
- Starts as sinusoidal shape laying on bottom of borehole
- More load starts the pipe snaking up the sides of the borehole
- Eventually, pipe winds into a helical shape (spring shaped)
- Lock up occurs
Mud Weights for Directional Drilling

- Mud Weight Increasing
- Deviation Increasing
- Hole Collapse
- Unstable
- Fracturing

Diagram showing the relationship between mud weight and deviation, with increasing mud weight leading to unstable conditions and hole collapse, while increasing deviation leads to fracturing.
Cuttings Beds

- Laminar cleaning
- 0 to 25 degrees
- 25 to 65 degrees
- Turbulent cleaning
- > 65 degrees

Cuttings bed
Drill Pipe Stress

- Tension due to hookloads
- Bending
- Compression
- Torsion
- Tension due to drill collars
Cementing Issues

• Annular settling
  – Free water on highside

• Centralization
  – Difficult to achieve

• Reciprocation
  – May not be possible
Directional Drilling Planning

- Surface coordinates
  - Latitude and longitude
  - Local grid coordinates
- Target
  - TVD
  - Boundaries
- Limitations
  - Lease lines
  - Other wellbores
- Hole and casing sizes
- Casing points
- KOP
- Maximum build and drop rates
- Geology
- Mud weights and type
- Offset information
  - Directional performance of BHA
  - Dips
- Geological sequence
- Rig information
  - Drill string
  - Mud Pumps
  - Mast strength
- Well profile
- Offset histories
Wellbore Profile

- **S-profile more difficult than slant profile**
  - More hole to be drilled
  - Drop off restricts WOB and rate of penetration (ROP)
  - Not as responsive to directional control
  - More drag

- **S-profile used when:**
  - Intermediate targets
  - Wellbore must be vertical in reservoir
Horizontal Drilling

- Any 90° hole
- Technology has caught up with idea
- Continuous improvements
  - Directional control
  - Reduced costs
- Utilizes
  - Geosteering
  - MWD and LWD
  - Underbalanced drilling
- Reservoir analysis techniques are starting to catch up with drilling technology
Requirements for Horizontal Boreholes

• Hit the target
• Smooth turns and builds for long reach
• Gauge borehole for problem-free drilling
• Minimal formation damage
• Reasonable cost
Approaches to Horizontal Drilling

<table>
<thead>
<tr>
<th>TYPE</th>
<th>RADIUS</th>
<th>BUILD ANGLE</th>
<th>CURVE LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERY SHORT</td>
<td>2'</td>
<td></td>
<td>3'</td>
</tr>
<tr>
<td>SHORT</td>
<td>40'</td>
<td>1.5°/FT</td>
<td>63'</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>266'</td>
<td>20°/100 FT</td>
<td>460'</td>
</tr>
<tr>
<td>CONVENTIONAL</td>
<td>2500'</td>
<td>2°/100 FT</td>
<td>4400'</td>
</tr>
</tbody>
</table>
Multilateral Drilling

- **Multilateral wells**
  - Single trunk
  - Multiple laterals (sometimes called branches or drainholes)
  - Can be vertical, horizontal, or deviated
- Able to reach multiple targets in same formation
- Laterals can be completed separately
- Large drainage area for small environmental footprint
- Difficult to operate
  - Operations
  - Stimulation
  - Production
- Potentially expensive
Extended Reach Drilling

1 Mile Deep

6.3 Miles (33,184 ft) Displacement

1,605 m
Extended Reach Drilling

• Long near-horizontal borehole
• Useful for environmentally sensitive areas
  - BP at UK Wytch Farm field
  - Up to 10 kilometers (6.2 miles)
• Only one location
  - Minimizes rig footprints

• Issues
  - Torque limitations
  - Hole instabilities
  - Cuttings transport
  - Not horizontal
  - Cannot slide
  - Equivalent circulating density (ECD) high
  - Casing running
    • Floated?
  - Swab and surge
Directional Drilling Costs

- Additional costs for directional drilling equipment
  - Mud motor, MWD, people, etc. $10,000/day
- Rig may need to be larger making for a larger location
  - Larger mud pumps, need more flow
- Casing and tubing design
  - Ovality and bending stress
- Additional mud cost and solids control equipment
  - Mud weight is usually higher
  - Cuttings bed development
- Additional borehole risk
  - Tectonic stress directions
- Slower ROP, more time on location
- Torque and drag higher
Thank you.

Any Questions?