TOOL/ROCK INTERACTION MODELLING for
ROP OPTIMIZATION in
DEEP HARD ROCK PERCUSSIVE DRILLING

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13th September, Celle Drilling 2016, Celle, Germany
What is SINTEF?

«Technology for a better society»

Scandinavia's largest independent non-profit research organization

- 2000 Employees
- 70 Nationalities
- 3800 Customers

Applied research, technology & innovation

- Renewable energy
- Ocean space
- Industry
- Materials
- Climate & environment
- Oil and gas
- Health and welfare
- ICT

What is INNO-Drill?

Technology platform for research-based innovations in deep geothermal drilling

- 4-years project (2016-2019)
- 2.6 M€ total budget
- 1 PhD + 1 PostDoc
INNO-Drill objectives

1) Reduce hard rock drilling cost by
   ✓ innovative drilling solutions
   ✓ better rate-of-penetration
   ✓ reduced tool wear

2) Establish a well documented Multiscale/multiphysics methodologies for the tool/rock interaction

Blog link: innodrill.wordpress.com / Previous project: nextdrill.wordpress.com
## ROP optimization

### EXPERIMENTS

<table>
<thead>
<tr>
<th>Rock material</th>
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<tbody>
<tr>
<td>Characterization of behaviour: effect of pressure, temperature, rate, fracture...</td>
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</table>

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<tr>
<th>Tool/rock interaction</th>
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<tbody>
<tr>
<td>Characterization of BRI laws: effect of repetition, indexation, cleaning, impact energy, rate, pressure...</td>
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<tr>
<th>Dynamic systems</th>
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<tbody>
<tr>
<td>Middle- and full-scale: assess the performance of percussive system in terms of ROP and BRI</td>
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### SIMULATIONS

<table>
<thead>
<tr>
<th>Rock Meso-models</th>
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<tbody>
<tr>
<td>(FEM, SPH)</td>
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<tr>
<th>Tool/Rock Meso-models</th>
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<td>Validation and extension out of laboratory ranges</td>
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<tr>
<th>Macro-models</th>
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<tr>
<td>Analytical/numerical predictions: parametrical study ROP = f(frequency, WOB, RPM, pressure,...)</td>
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Dynamic confined tests

Purdue Univ. - Tampere UT - SINTEF

- Kuru granite rock samples
- Split Hopkinson Pressure bars with radial pressure chamber

- Strain rate = 600 s\(^{-1}\)
- Confinement up to 225 MPa
- Comparison with static tests (confinement up to 100 MPa)

Hokka et al., 2016. *International Journal of Impact Engineering* 91, 183-193
Bit/Rock interaction laws

SINTEF - Tampere UT - UMN

- Sequential drop tests
- Indexable granite block
- 7-buttons drillbit
- Series: 10-17 tests
- Impact energy: 13-34J
- Index. angles: 10-20°

- Volume of removal (stereolithography of surface replicat) → MSE comparison

- BRI curves: experimental vs. numeric

- Finite Element Analysis of drop tests:
  2 rock surface shapes:

Surface replicat
Damage plots

Fourmeau M., Kane A., Hokka M., 2016. *Philosophical Transactions A, Manuscript submitted*
Chip hold down

Master internship Gaspar Gohin (March to July 2016)

- Chip life: fluid equations

- ROP (regrinding) prediction

<table>
<thead>
<tr>
<th>Characteristic time</th>
<th>$O(\alpha)$</th>
<th>Chip equation</th>
<th>Hypothesis</th>
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</thead>
<tbody>
<tr>
<td>Cavitation</td>
<td>$\tau_{\text{cav}} \sim \frac{L}{2} \sqrt{\frac{P_0}{\eta}}$</td>
<td>$\rho_s \dot{e} \approx -P_0 + p_{\text{cav}}$</td>
<td>$\epsilon &lt; 1$</td>
</tr>
<tr>
<td>Fluid sticktion</td>
<td>$\tau_{\text{st}} \sim \frac{L}{2 \eta} \left( \frac{L}{2} \right)^2$</td>
<td>$\rho_s \dot{e} \approx -\eta \dot{\epsilon}^2 + \rho_b$</td>
<td>$Re &lt; 1$</td>
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<tr>
<td>Turbulence</td>
<td>$\tau_{\text{tur}} \sim \frac{3\eta L \dot{\epsilon}}{2}$</td>
<td>$\rho_s \dot{e} \approx \frac{3}{2} \rho C_d (U_0 - \dot{e})^2$</td>
<td>$Re &gt;&gt; 1$</td>
</tr>
</tbody>
</table>
Laboratory drilling tests

SINTEF – Resonator AS

- Hydraulic hammer
  Hycon HH20
- Hex rod 22-5’-12°
- Ø33mm 7-buttons bit
- Air flushing (dry)
  & side flushing plugged

- 8 tests: impact energy, RPM, WOB, frequency

<table>
<thead>
<tr>
<th>Test</th>
<th>$f_p$</th>
<th>RPM</th>
<th>$F_p$</th>
<th>$f$</th>
<th>$E_{imp}$</th>
<th>ROP</th>
<th>MSE</th>
<th>$\Delta \theta$</th>
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<tbody>
<tr>
<td>n°</td>
<td>[Hz]</td>
<td>[tr/min]</td>
<td>[bar]</td>
<td>[Hz]</td>
<td>[J]</td>
<td>[mm/min]</td>
<td>[J/cm$^2$]</td>
<td>[°]</td>
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<tr>
<td>3</td>
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<td>12</td>
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<tr>
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<td>18</td>
<td>85</td>
<td>0.75</td>
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<td>25.89</td>
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<td>0.55</td>
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<tr>
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<td>243</td>
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<tr>
<td>22</td>
<td>18</td>
<td>45</td>
<td>0.55</td>
<td>19.7</td>
<td>41.0</td>
<td>193</td>
<td>294</td>
<td>13.71</td>
</tr>
</tbody>
</table>

- Bit/rock interaction and ROP
  Force vs. displacement
  Avancement

  Some conclusions:
  - RPM has a significant effect (25% ROP ↑)
  - MSE is lower at higher impact energy

Hoang HN, Keskiniva M, 2016. ROP drilling tests at Resonator AS, SINTEF report F27522
Control of DTH hammer

PhD topic NTNU-UMN-SINTEF (planned for 2017-2019)

1) Modeling of Percussion Drilling System

3) Bit-Rock Interface (BRI): experimental Work
   - Link indentation to effective displacement (to account for pressure and cleaning quality)

- Impact velocity
- Indexation
- Frequency
- Pressure
- ...

Using Simplified BRI laws:

Physica D: Nonlinear Phenomena 258, 1-10

2) Real-time Measurements and Control
   - Optimize process using current technology
   - Measure relevant observers for control
   - Design controller that acts on fluid pressure/flow (assuming optimal conditions are understood)

Saksala et al., 2014
Thank you for your attention!