Traction Prediction of a Smooth Rigid Wheel in Soil Using Coupled Eulerian-Lagrangian Analysis

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Agenda

• Problem Definition
• What is soil?
• Physics of Soil Deformation
  – Permanent deformation, instabilities, etc
• Modeling Soil
  – Continuum approach
• Analysis of Rigid Wheel
• Summary
Problem Definition

**Big Problem:** Predict traction performance of a tire in the field
- Improve mechanistic understanding of tire traction performance
- Improve product performance
- Reduce development cycle time

**Smaller Problem:** Predict traction of a rigid wheel in “controlled” soil
- Removed pneumatics of the tire
- Removed lugs/complex geometric features of a tire
- Soil is well controlled

Acceleration due to gravity, 9.81 m/s²
What is Soil? - 1/3

- Clay (< 0.002 mm)
- Silt (0.05 to 0.002 mm)
- Sand (2 to 0.05 mm)
- Gravel (> 2 mm)

Particle Size Distribution [mm]

Percentage Finer [%]

Decatur Clay Loam
Norfolk Sandy Loam
Hiwassee Clay
What is Soil? - 2/3

Moisture/Liquid affects the strength of soil significantly

Dry beach sand flows like water
Mud (saturated soil) also flows like water

Moist sand/soil is stronger than uncompacted (or loose) dry soil and mud (due to surface tension of water)

<table>
<thead>
<tr>
<th>Solid</th>
<th>Liquid</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>[2 to 0.05 mm]</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
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<td></td>
</tr>
<tr>
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<td>[&lt;0.002 mm]</td>
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</table>
What is Soil? - 3/3

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<tr>
<th>Solid</th>
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<tbody>
<tr>
<td>Sand [2 to 0.05 mm]</td>
<td>Moisture/Liquid affects the strength of soil significantly</td>
<td>Air (voids) is a measure of compaction/voids in soil.</td>
</tr>
<tr>
<td>Silt [0.05 to 0.002 mm]</td>
<td></td>
<td></td>
</tr>
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<td></td>
</tr>
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</table>
Physics of soil deformation

Loading

Volumetric compression;
(permanent initially)

Shearing deformation
(permanent)

Further Loading

Max. density achieved
(only shearing deformation)

- Soil becomes denser and stiffer
- More available traction
- Important for soil compaction & traction

- Critical State (shear failure / instability – landslide)
- Important for max. available traction

AGV – 04/30/2012
Approaches to Modeling Soil

Approach #1

Model individual particles

Challenges:
- Clay particles are < 0.002 mm → 1 mm³ of soil will contain ~ 10⁶ particles
- Capturing effect of moisture and other microscopic interactions

Approach #2

Model soil as a continuum

Notes:
- Only average behavior of soil is captured
- Individual particles, clumps in soil are ignored
- Applicable only if smallest finite element is much larger than largest soil particle

Advantages:
- Can use continuum mechanics
- Use FEA to solve governing equations
- Practical
Physics to be Modeled

Very large deformations
Continuum mechanics
Eulerian formulation of balance laws in soil

Permanent deformations
Theory of plasticity (soil model)

Instabilities
Theory of plasticity (part of soil model)
Explicit analysis

Lagrangian: speedometers inside a car
Eulerian: sensors on the road

1-D Model of Soil

Spring

Non-linear slider
Soil Model – 1/3

1-D Model of Soil

Spring

Pressure hardening of sliding

3-D Model of Soil: Yield Surface

Component 1: Normal Consolidation Curve

Pressure vs. soil compaction curve
This function determines soil compaction
1-D Model of Soil

- Spring
- Shear failure of slider
- shear

3-D Model of Soil: Yield Surface

**Component 2: Shear Failure Surface**

- Determines when soil fails (flows like a liquid)
- Direct influence on traction
Verification of Soil Models

1. Mod. Drucker-Prager/Cap (ABAQUS)

- Shear failure surface
- Loading Path

Mod. Drucker-Prager soil model is reasonable
- in this loading path
- other loading paths not shown here

Norfolk Sandy Loam
National Soil Dynamics Lab (@ Auburn)

Top of soil bins & testing facility

Indoor soil bin

Single wheel traction tester
Problem Definition - Validation

Rigid Wheel Rolling on Soil

**Test Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Load [kN]</td>
<td>2.9, 5.8, 8.7, 11.6</td>
</tr>
<tr>
<td>Slip Rates [%]</td>
<td>11.1, 23.0</td>
</tr>
<tr>
<td>Rolling Speed [m/s]</td>
<td>0.15</td>
</tr>
<tr>
<td>Wheel Size</td>
<td>1.372 m x 0.305 m</td>
</tr>
<tr>
<td>Soil Bin Size</td>
<td>57.3 m x 6.1 m x 1.8 m</td>
</tr>
</tbody>
</table>

**Test Output**

- Net Traction
- Rut Depth
- Stresses beneath soil surface

Mechanics of Traction

Normal Contact Forces

- **Motion Resistance**
  \[ T_{+ve}^p + T_{-ve}^f \]
  - Contact pressure
  - Frictional

Tangential Contact Forces

- **Net Traction**
  \[ T_{+ve}^p + T_{+ve}^f - T_{-ve}^p - T_{-ve}^f \]
  - Contact pressure
  - Frictional
Total Strain on Cap Surface (PEQC2)

Norfolk Sandy Loam
Load = 11.6 kN
Slip Rate = 11%

Predicts the slip plane under soil
Permanent deformation of soil
Strain has reached 2,700%
Traction Validation – Norfolk Sandy Loam

\[ y = 1.0517x - 0.0764 \]
\[ R^2 = 0.9672 \]

Very good comparison between predicted and measured net traction

Predictions underestimate effect of slip rate

Other data points for rut depth are not available
Very good comparison between predicted and measured net traction

Predictions underestimate effect of slip rate
Summary

• Problem: Predict traction of a rigid wheel rolling in soil

• Continuum approach to solve the problem
  – Used continuum mechanics, theory of plasticity, & FEA
  – Verified ABAQUS soil model

• Analysis of Rigid Wheel Rolling on Soil
  – Solution predicted presence of slip surfaces
  – Predicted and measured traction and rut depth compared very well
  – Shows that continuum approach can be applied to soil
Thank You

Questions