STRENGTH OF SOIL DEPOSITS ALONG MER TRAVERSES

L. Richter¹ and the MER Athena Science Team

¹: DLR Institute of Space Simulation
Two traverses on Mars

Spirit Rover Traverse Map (Sol 343)
Wheel tracks from orbit

MER-A

MOC R20-01024

300 m

MER-B

MOC R16-02188

100 m

Eagle Crater

Fram Crater

Endurance Crater

Lander

Rover track

Rover

Landing rocket blast effects

Mars Exploration Rover
• Relevance of physical properties: knowledge of strengths of soils and rocks, and observation of physical processes, to:
  – identify different materials from their strengths
  – compare physical and compositional properties
  – correlate materials with geologic units
  – identify stratigraphic relationships
  – identify modification and transport processes
• No dedicated instruments -> works across multiple disciplines and payload elements
• Reported here: soil strength and other properties from wheel sinkage
MER-A Sol 61 Legacy Pan
(Middle Ground Hollow)

- Dust veneer (variable)
- Bright crust (few mm thick)
- Relatively darker subsurface soil
Soil crusts evidence

MER-A Sol 51 PANCAM

MER-A Sol 72 PANCAM

MER-B Sol 62 MIB

30 mm
, 'Opportunity' wheel tracks

MER-B Sol 324 NAVCAM
Tracks PANCAM observations

MER-A Sol 42 'True Color'

MER-B Sol 373
Tracks MI observations

MER-A Sol 122 FHAZCAM

MER-A Sol 122 MI (wheel tracks)

30 mm
Soil strength from wheel sinkage

- Measure wheel rut depth in stereo images (< 1 mm error in near-field)
- Wheel-soil theory calibrated for MER wheel: obtain soil strength parameters for vertical loading
- Compare with known soils: estimation of soil strength parameters for shear loading
- Results applicable to upper 20-30 cm of soil (stress dissipation for wheel width)
- Soil strength -> correlated with bulk density -> correlated with thermal inertia and dielectric properties -> comparison with datasets from orbital missions/remote sensing
Soil strength from wheel sinkage

Mars Exploration Rover

MER-A Sol 15 RHAZ

- Shallow depression (from stereo)
- Superimposed front & rear wheel track
- Area of sinkage analysis

~30 mm sinkage

Center wheel track
Systematic rut depth results

MER-A (through Sol 103)
Soil strength from wheel sinkage

- Wheel slip estimate from traverse reconstructions (absolute localization vs. wheel turns) -> account for wheel slip-sinkage
- Relation between wheel dimensions ($D, b$), wheel load ($W$), soil parameters for vertical loading ($k_c, k_\phi, n$) and load-sinkage $z_0$:

$$W = -b \cdot k^* \cdot \int_0^{z_0} z^n \frac{2(z_0 - z) - D}{2\sqrt{D(z_0 - z)(z_0 - z)^2}} \, dz$$

$$k^* = \frac{k_c}{b} + k_\phi$$

- Caveat: no unique solution for $k^*$
- Ways out:
  - Additional loading surface in same soil unit (Mössbauer contact plate)
  - Comparison with known soils -> also gives values for shear strength parameters by analogy
MB ,noseprint‘

MERMER--A Sol 65 ‘True Color‘

MER-A Sol 65 ‘True Color‘

MER-A Sol 65 MI

30 mm
Example: MER-A egress soil

- Solving for $k^*$ for different values of $n$ (exponent of soil deformation for vertical loading):

<table>
<thead>
<tr>
<th>Soil</th>
<th>n</th>
<th>$k_c$ [N/m$^{n+1}$]</th>
<th>$k_{phi}$ [N/m$^{n+2}$]</th>
<th>$k^*$ [N/m$^{n+2}$] (for b=160 mm)</th>
<th>$\phi$ [°]</th>
<th>$c$ [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand (Land Locomotion Laboratory)</td>
<td>1.1</td>
<td>9.90E+02</td>
<td>1.53E+06</td>
<td>1.53E+06</td>
<td>28</td>
<td>1.04</td>
</tr>
<tr>
<td>Sandy loam (Land Locomotion Laboratory)</td>
<td>0.7</td>
<td>5.27E+03</td>
<td>1.52E+06</td>
<td>1.55E+06</td>
<td>29</td>
<td>1.72</td>
</tr>
<tr>
<td>Sandy loam Michigan (Strong, Buchele)</td>
<td>0.9</td>
<td>5.25E+04</td>
<td>1.13E+06</td>
<td>1.46E+06</td>
<td>20</td>
<td>4.83</td>
</tr>
<tr>
<td>LETE sand (Wong)</td>
<td>0.79</td>
<td>1.02E+05</td>
<td>5.30E+06</td>
<td>5.94E+06</td>
<td>31.1</td>
<td>1.30</td>
</tr>
<tr>
<td>DLR mechanical Mars soil simulant</td>
<td>0.8</td>
<td>5.79E+03</td>
<td>1.80E+05</td>
<td>2.16E+05</td>
<td>17.8</td>
<td>0.30</td>
</tr>
<tr>
<td>Lunar nominal soil</td>
<td>1</td>
<td>1.40E+03</td>
<td>8.20E+05</td>
<td>8.29E+05</td>
<td>35</td>
<td>0.17</td>
</tr>
<tr>
<td>Sandy loam (Land Locomotion Laboratory)</td>
<td>0.2</td>
<td>2.56E+03</td>
<td>4.31E+04</td>
<td>5.91E+04</td>
<td>38</td>
<td>1.38</td>
</tr>
<tr>
<td>Sandy loam (Hanamoto)</td>
<td>0.3</td>
<td>2.79E+03</td>
<td>1.41E+05</td>
<td>1.59E+05</td>
<td>22</td>
<td>13.79</td>
</tr>
<tr>
<td>Clayey soil (Thailand)</td>
<td>0.5</td>
<td>1.32E+04</td>
<td>6.92E+05</td>
<td>7.75E+05</td>
<td>13</td>
<td>4.14</td>
</tr>
<tr>
<td>Heavy clay (WES)</td>
<td>0.11</td>
<td>1.84E+03</td>
<td>1.03E+05</td>
<td>1.15E+05</td>
<td>6</td>
<td>20.69</td>
</tr>
</tbody>
</table>
Example: MER-A egress soil

- Apply bearing capacity theory to derive bearing strength

\[ W'_c = 2\gamma_s l \cdot b^2 N'_\gamma + 2l \cdot b \cdot qN'_q + \frac{4}{3} l \cdot b \cdot cN'_c \]
Some results and comparisons

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Bearing strength</th>
<th>Cohesion</th>
<th>Internal friction angle</th>
<th>Bulk density (soil)</th>
<th>Thermal inertia (soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gusev loose soils</strong></td>
<td>5 kPa</td>
<td>1 kPa</td>
<td>20°</td>
<td>1230 kg/m³</td>
<td>134 J m⁻² s⁻¹/² K⁻¹</td>
</tr>
<tr>
<td><strong>Gusev dense soils</strong></td>
<td>200 kPa</td>
<td>15 kPa</td>
<td>25°</td>
<td>1483 kg/m³</td>
<td>153 J m⁻² s⁻¹/² K⁻¹</td>
</tr>
<tr>
<td><strong>Meridiani Eagle crater floor &amp; M. plains</strong></td>
<td>80 kPa</td>
<td>5 kPa</td>
<td>20°</td>
<td>1333 kg/m³</td>
<td>142 J m⁻² s⁻¹/² K⁻¹</td>
</tr>
<tr>
<td><strong>Meridiani Eagle crater wall (loose soil)</strong></td>
<td>8 kPa</td>
<td>0.5 kPa</td>
<td>20°</td>
<td>1186 kg/m³</td>
<td>130 J m⁻² s⁻¹/² K⁻¹</td>
</tr>
<tr>
<td><strong>VL-1 ‘drift’</strong></td>
<td>1.6±1.2 kPa</td>
<td>18±2.4°</td>
<td>1150±150 kg/m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VL-1 ‘blocky’</strong></td>
<td>5.5±2.7 kPa</td>
<td>30.8±2.4°</td>
<td>1600±400 kg/m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MPF ‘cloddy’</strong></td>
<td>0.17±0.18 kPa</td>
<td>37.0±2.6°</td>
<td>1530±110 kg/m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lunar soil (inter-crater areas)</strong> (Kemurdjian et al., 1978)</td>
<td>36-55 kPa</td>
<td>2.7-3.4 kPa</td>
<td>22-27°</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coarse sand (Earth)</strong></td>
<td>150-300 kPa</td>
<td>0.1-2.0 kPa</td>
<td>30-39°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*) assuming behavior like lunar regolith: \( \tan \phi = 0.725 \times \frac{1}{E} \), \( c = 0.720 \times E^{(-5.664)} \)

**) assuming \( k = 0.01 \text{ W m}^{-1} \text{ K}^{-1} + [6.4 \times 10^{-6} \text{ m}^4 \text{ s}^{-3} \text{ K}^{-1}] \rho \), and \( c_p = 820 \text{ J kg}^{-1} \text{ K}^{-1} \)
Wheel trenching

MER-B Sol 54

MER-B Sol 73

MER-A Sol 139
Mars Exploration Rover

MER-B Sol 73 trench

mean current vs. time (10% winsorized mean)

-> being used to infer soil shear strength vs. depth
On-going: mapping of results along traverses
- correlations with local geology
- comparisons with thermal inertia and other quantities inferred from remote sensing
Implications

- Soil deposits with distinct mechanical properties
- Cohesion inferred for all soil types observed with the described methods
- Soil thermal inertia retrievals: slightly lower than fine-component TI from orbital measurements? (comparisons in progress, also with Mini-TES derived TI)
- Soil crusts formation as recent or modern process (action of moisture & salts?)