PRELIMINARY REPORT ON THE DEVELOPMENT OF ANALYSIS METHODS TO DETERMINE MARS SOIL MECHANICAL PROPERTIES FROM LABORATORY TESTS, DISCRETE PARTICLE MODELING, AND MARS TRENCHING EXPERIMENTS. J.B. Johnson[1], A.F.C. Haldemann[2], M.A. Hopkins[1], J. Moore[3], J. Peters[1], R.J. Sullivan[4], and the Athena Science Team. [1]U.S. Army Engineer Research and Development Center (Jerome.B.Johnson@erdc.usace.army.mil); [2]Jet Propulsion Laboratory, California Institute of Technology; [3]NASA Ames Research Center; [4]Cornell University.

Introduction: Accurate characterization of Mars soil physical properties and their heterogeneity are essential to addressing local surface geologic processes and conducting engineering analysis for future landed missions. Both geologic process interpretation and engineering analysis are influnced by scale dependent "effective" values of soil properties, which depend on both material property and spatial variations (**Fig. 1**).

Figure 1. Erosion ruts exceeding 10 cm were created when the Opportunity rover was trapped for five weeks in at Purgatory Dune (NASA/JPL).

Analysis methods that utilize terrestrial laboratory tests and discrete element methods are being developed to analyze MER traverse tracks, and trenching and indentation experiments to determine soil physical and mechanical properties and their heterogeneity.

Background: Traditional techniques to estimate Mars soil mechanical properties were developed using the results of Viking missions and the Sojourner rover at the Pathfinder site [1—9]. These include the analysis of data from footpad impressions, extendable surface samplers to dig and plough into Martian soil (Viking missions) and rover wheel impressions, and wheel trenching activities (Pathfinder – Sojourner rover). Estimates of the force acting on the extendable arm, or torque on the rover wheels were made from motor currents. In combination with images of soil disturbances from testing, forces were used to estimate soil cohesion and internal friction parameters using the Mohr-Coulomb soil strength model.

These traditional techniques can produce derived values of soil property values that yield different results depending on the test method employed. These differences are not related to experimental uncertainty, but depend on the geometry of the test method and the accuracy of analysis models used to interpret the measurements. Different test geometries impart different stress and deformation fields at the soil microscale that may not be captured by these simple traditional model analyses methods. The use of discrete element methods (DEM) can greatly reduce the uncertainy of derived soil properties by explicitely capturing the influences of test geometries and soil partille behavior.

Approach and Technique: The primary MER data available for use to derive soil properties include like-wheel trenching in soil (**Fig. 2**), development of drag piles, wheel tracks (**Fig. 1**), and Mössbauer contact plate indentation.

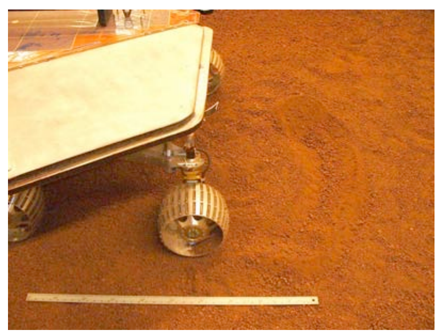

Figure 2. Example arch trenching experiment at the Jet Propulsion Laboratory Mars test facility (Haldemann).

Interpretation of wheel trenching tests proceeds by first analyzing wheel current motors to estimate wheel torque during MER trenching events. Terestrial laboratory tests using an equivalent MER wheel and a simulant of Mars regolith are used to calibrate MER wheel torqure/electric current relationships. Laboratory trenching tests provide data that can be used to calilbrate discrete element model simulations under terrestrial conditions. Once calibrated, DEM simulations can be applied to MER trenching tests. Similar DEM analyses can be applied to other MER soil property tests. The influence of Mars gravity, test geometry, and material property and spatial heterogeneity, can all be included in an analysis region to examine properties of soil cohesion, internal friction, grain size and density.

The Value of Discrete Element Methods: The DEM is a technique for explicitly modeling the dynamics of assemblies of particles. It is particularly useful when a material undergoes large-scale discontinuous deformations that depend on micro-scale contact processes, internal breakage of contact bonds, and compaction of broken fragments.

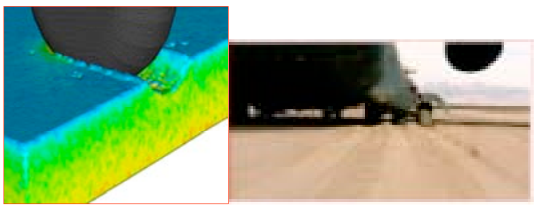

Figure 3. DEM 10 million particle simulation of aircraft tire traveling through sand (Peters).

The DEM approach allows for the use of complex particle contact physics. The DEM stores the particle shapes, velocities, and locations; finds contacts; calculates forces and moments at each contact; calculates the conditions of contact bond formation, growth, and rupture; and calculates the movement of each particle within the aggregate [10, 12].

For MER analyses, the important geometric aspects of a specific soil test (e.g., Mössbauer contact plate, indentation, wheel compaction or trenching) can be represented by the DEM, along with the soil properties (grain size, and particle contact cohesion and friction) to directly represent the experiment of interest. Once these micro-scale parameters are known the model can be used to examine specific MER equipment behaviors to better understand their cause (e.g., what factors contributed to Opportunity getting stuck in Purgatory Dune). Upperbound estimates of grain size for fines can be determined using DEM simulations by decreasing the particle size used in the model until the simulation output replicates the fidelity of an indentation or wheel track image [12]. Observed heterogeneity can be included into DEM simulations to examine scale effects due to physical property and spatial variability. Experience indicates that that when DEM simulations accurately replicate test conditions, selected granular material properties are very close to their actual values.

Conclusions: Terrestrial laboratory tests of Mars regolith simulant properties and of MER tests combined with DEM simulatations are being developed to derive soil properties from MER wheel trenching, Mössbauer contact plate indentation, and other soils tests. The addition of DEM simulation capability significantly reduces uncertainties in derived data caused by test geometry, micro-scale particle interactions, and material heterogeneity. We intend to present initial resuts of our DEM work.

References: [1] Moore, H.J., et al. (1977) *J. Geophys. Res*. 82, 4497. [2] Moore, H.J., et al. (1979) *J. Geophys. Res*. 84, 8365. [3] Moore, H.J., et al. (1982) *J. Geophys. Res*. 87, 10043. [4] Moore, H.J., et al. (1987) U.S. Geol. Surv. Prof. Paper 1389. [5] Moore, H.J., et al. (1999) *J. Geophys. Res*. 104, 8729. [6] Arvidson, R.E. et al. (1989) *Rev. Geophys. Space Phys*. 27, 39. [7] Rover Team (1997a) *Science* 278, 1765. [8] Rover Team (1997b) *J. Geophys. Res.* 102, 3989. [9] McKyes, E. and O.S. Ali (1977) *J. Terramechanics* 14, 43. [10] Cundall, P.A. and O.D.L. Strack (1979) *Geotechnique*, 29, 47. [11] Hopkins, M.A. (2004) *J. Engng. Comput.*, 21, 422, doi: 10.1108/02644400410519866. [12] Arvidson, R.E., et al. (2004) *Science* 306, 1730.