MARS GLOBAL SURVEYOR SOIL MECHANICS DATA ANALYSIS

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Abstract
An investigation is in progress to evaluate the bearing capacity, trafficability, and shear strength of Martian regolith by analysis of Mars Global Surveyor (MGS) photographs and laser altimeter (MOLA) measurements. Types of analysis include computer modeling of landslides, natural slope stability calculations, angle of repose measurements, depth of boulder tracks, and height of vertical slopes. Ongoing analysis of soil mechanics data is necessary to better define the design parameters needed for future landing site selection and to engineer landers, rovers, sampling devices, and other equipment for interaction with the Martian surface during future exploratory missions. The thrust of the current investigation is the evaluation of high priority landing sites for the Mars 2003 twin MER mission.

Introduction
Mars soil mechanical properties affect the ability of spacecraft to land on and explore the Martian surface. Mars soil mechanical properties also affect geomorphological processes such as mass wasting, crater formation, and erosion, which are important factors in understanding Mars surface layer evolution. Determination of Mars soil mechanical properties will improve future lander mission success and provide parameters for geomorphologic modeling.

Mars Global Surveyor high resolution photographs and laser altimeter measurements provide unique data for performing a number of valuable soil mechanics analyses. A soil mechanics investigation is underway wherein soil mechanical properties are being determined by computer modeling of mass wasting features, analysis of natural slope stability, analysis of boulder tracks, measurement of vertical slope height, and measurement of the angle of repose of slope debris. The

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results of these analyses will be compared with thermal inertia and albedo measurements and with geologic maps in an attempt to establish correlations. Conventional geotechnical engineering principles will be applied to estimate ultimate bearing capacity, dynamic penetration resistance, angle of critical slope stability, and rover trafficability for various soil types on Mars.

The objective of this investigation is to assess hazards such as unstable slopes and compressible soils for future landing site selection and to provide engineering input for the design of landers, rovers, sampling devices, and other equipment that will interact with the Martian surface during future exploratory missions. Furthermore, the results can be used as input parameters for modeling many geological and geomorphological processes important to understanding the evolutionary history of Mars. The thrust of the current investigation is the evaluation of high priority landing sites for the 2003 twin Mars Exploration Rover mission.

**Methodology**

There are numerous soil mechanics properties including shear strength, compressive strength, bearing capacity, penetration resistance, coefficient of consolidation, and modulus of elasticity. Fortunately, almost all soil mechanical properties are interrelated by fundamental methods of mechanics of materials. A practical example of this is the use of standard penetration resistance to determine bearing capacity. Thus, it is possible for geotechnical engineers to use observations of one aspect of soil mechanical behavior to estimate a more complete set of soil mechanical properties. For example, astronaut footprints and spacecraft footpad penetrations were used to estimate the depth to which a vertical trench could be hand excavated by an Apollo 15 astronaut (Mitchell et al., 1972).

As in most terrestrial geotechnical engineering projects, the current Mars soil mechanics investigation focuses on determination of the mechanical property of shear strength. Established and reliable correlations exist between shear strength and other mechanical properties of soil. Soil shear strength is typically represented by the linear Coulomb failure envelope on the Mohr stress diagram. From the cohesion, angle of internal friction, and the state of effective stress for a particular location in soil, one can determine ultimate bearing capacity, dynamic penetration resistance, the angle of critical slope stability, rover trafficability, and a number of other parameters important to Mars exploration and geomorphological modeling.

Mars Global Surveyor high resolution photographs show a number of geographic and geologic features that can be analyzed to determine soil shear strength. Of particular interest, are the numerous landslide features apparent on the Martian surface. In common geotechnical laboratory tests, soil is sheared to determine shear strength (i.e. vane shear, direct shear, and triaxial shear). A landslide is a natural manifestation of a large scale, in situ, shear strength test. Analysis of landslide features is one of the most accurate techniques for macro shear strength determination and is used frequently by geotechnical engineers for investigations on Earth. The current soil mechanics investigation focuses on this type of analysis. To supplement this analysis, a number of other features apparent in Mars Global Surveyor high resolution photographs will be considered including natural slope stability, depth of boulder tracks, vertical slope heights, and angles of repose of slope debris. Specific descriptions of the ongoing analyses follow.
Landslides

There are five kinematically distinct types of landslide movements shown in Fig. 1. The surface of Mars exhibits several of these types of landslides. Each landslide has a distinct slip surface where movement has occurred. The slip surface can be interpreted and defined from review of MGS photographs and MOLA topographic information. Once the slip surface is defined, modern slope stability analysis software can be incorporated to parametrically determine the shear strength in the stratum where the failure occurred.

As an example, a set of landslides which occurred during the period of Mars Global Surveyor observation are shown in Fig. 2. For the analysis, general topography in the landslide area is being obtained from MOLA measurements. Length of the scarps is being scaled from MGS photographs. Approximate depth and geometry of the landslide slip surfaces is being estimated from the observed shadowing and known angle of the sun. Previous literature on the geology of the specific site, where available, is being consulted to determine if there is justification for soil layering and at what depths such layering might be present. Bedrock depth is being determined from regional radar signal attenuation provided by Christensen (1986a). All of these data are being combined to model the landslide using software available in the engineering computer laboratories at Colorado State University. An example graphical model is shown in Fig. 3.
Parametric determination of shear strength parameters through slope stability analysis is not particularly sensitive to the assumed soil density especially in Mars gravity. Past radar reflectivity measurements, such as those by Harmon and Ostro (1985), at or near landslide features can be used to estimate soil density values that are sufficiently accurate to make reliable shear strength determinations.

**Natural Slope Stability**

In the crater wall shown in Fig. 2, all three landslides occur along a section of topography with uniform slope. A logical conclusion is that the entire slope is marginally stable. In other words, soil shear strength is approximately equal to destabilizing stresses (factor of safety $\approx 1.0$). Stability analysis of marginally stable natural slopes provides another method of determining soil shear strength. Where remnants of landslides exist with an obscured specific slip surface, the stability of
the natural slopes is being analyzed to obtain pairs of cohesion and angle of internal friction values that satisfy lower bound shear strength requirements for marginal stability. Besides areas of landslide remnants, natural slope stability analysis is being performed in regions where landslides are not prevalent, such as the comparatively smooth South polar layered terrain. By selecting the steepest slopes in the region, shear strength determinations, although still lower bound, begin to approach actual values. For the analysis, general topography in the area of natural slopes is being obtained from MOLA measurements and MGS photographs. Specific values of cohesion and angle of internal friction can be obtained by coupling natural slope stability analysis with another form of shear strength determination, such as analysis of boulder tracks, in order to focus on a specific pair of results.

**Boulder Tracks**

The presence of boulders on the Martian surface is a hazard at spacecraft landing sites. Consequently, many investigations have been performed to characterize the size and frequency of boulders and rock abundance in various areas of Mars (i.e. Christensen, 1986b). The presence of boulders also provides another means to evaluate soil shear strength. Although it is impossible to determine bearing capacity of soils beneath boulders due to the uncertainty of depth of burial, Hovland and Mitchell (1972) demonstrated a technique where they successfully determined the shear strength of lunar soils by analysis of boulder tracks shown in photographs from Orbiter missions to the Moon. Their technique consisted of determining the length, depth, and width of tracks created by the movement of boulders down natural slopes. Based on modifications to conventional bearing capacity equations, they were able to determine probable values of soil shear strength. In the review of MGS photographs, evidence of downslope boulder movements are being sought and the same type of analysis is being performed.

**Vertical Slope Heights**

Mars Global Surveyor photographs show occasional vertical to near vertical slopes. The height of vertical slopes can be used to determine lower bound estimates of soil and/or bedrock cohesion and angle of internal friction. Without soil layering or sloping overburden, the Culmann Method of analysis of finite slope with plane failure surface can be used. Culmann relates critical height, $H_{cr}$, to soil shear strength parameters. The tallest near vertical slopes in a region are being analyzed so that shear strength estimates, although still lower bound, begin to approach actual values. For the analysis, general topography in the area of near vertical slopes will be obtained from MOLA measurements and MGS photographs. Critical heights and slope angles will be estimated through considerations of sun shadowing and by interpolation between MOLA measurements.

**Angle of Repose**

The angle of repose of soil is another indication of shear strength and can be analyzed considering the stability of infinite slopes. Angle of repose generally applies to loosely deposited soil such as slope debris. It should be noted that the final angle that slope debris achieves is sometimes influenced by factors such as partial confinement, whereas “angle of repose” represents shear strength in a loose condition absent of external confining stresses. Furthermore, the angle of repose is representative of soil at near minimum density and may not be representative of undisturbed soils on
flat lying surfaces in the vicinity. Nonetheless, lower bound estimates of shear strength from angle of repose measurements are an important source of supplemental that should be incorporated into any planetary soil mechanics investigation. For cohesionless soil, the angle of repose is equal to the angle of internal friction. However, in Mars’ low gravity environment cohesion has a more significant role than on Earth and should not be assumed to be zero.

**Thermal Inertia, Albedo and Geology**

Christensen and Moore (1992) used remote sensing measurements to divide the Martian surface layer into 4 distinct units based primarily on thermal inertia and albedo. Areas of Mars covered by each unit are shown in Fig. 4. The properties of each unit are summarized below.

Unit 1 consists of active dust deposits described by several meters of fine dust particles overlying very rough bedrock. The surface has low rock abundance, low density, and bright-red color. Thermal inertia ranges from 1 to $3.5 \times 10^{-3}$ cm$^2$ s$^{-1/2}$ K$^{-1}$ and albedo ranges from 0.26 to 0.40.

Unit 2 consists of active coarse material described by dust free sand and larger sized particles. The surface has high rock abundance and black color. Thermal inertia ranges from 7.7 to $20 \times 10^{-3}$ cm$^2$ s$^{-1/2}$ K$^{-1}$ and albedo ranges from 0.1-0.2.

Fig. 4 Mars Surface Unit Map (Christensen and Moore, 1992)
Unit 3 consists of indurated surfaces described by cemented sand sized particles exhibiting high correlation between thermal conductivity and density. The surface has moderate rock abundance, is mostly dust free, and dark red color. Thermal inertia ranges from 3.5-7.7 x 10^{-3} cm^2s^{-1/2}K^{-1} and albedo ranges from 0.15 to 0.25.

Unit 4 consists of mixed coarse and dust materials described by a thin dust layer over indurated or rocky surfaces. The surface has moderate rock abundance and varies in color and density. Thermal inertia ranges from 5-9 x 10^{-3} cm^2s^{-1/2}K^{-1} and albedo ranges from 0.25 to 0.3.

Due to the considerable differences between soil and rock conditions in each unit, strong correlations between surface layer unit number and soil shear strength are anticipated. Determinations of Mars soil shear strength are being compared with MGS thermal inertia measurements and albedo measurements in order to derive these correlations.

Thermal inertia magnitudes can not be referenced simply from a global map since measurements are sensitive to local topography (Jakosky et al, 2000). By obtaining high quality thermal inertia measurements, it should be possible to subdivide major surface layer units into subcategories with specific thermal inertia and soil shear strength.

Within the major surface layer units, correlations between geologic features and soil shear strength are expected. Soil shear strength determinations will be compared with geologic classifications provided on maps by Scott and Tanaka (1986) and Greeley and Guest (1987). In addition, relationships between smaller geologic features and shear strength determinations (ie. crater wall, layered terrain, dune formations, canyon slope, etc) are being sought. Cognizance of area geology may improve the ability to subdivide major surface layer units into subcategories with specific thermal inertia and soil shear strength. The ultimate objective is to provide recommended values of soil shear strength based on thermal inertia, albedo, and local geology.

Other Mechanical Properties

Using soil shear strength determined for various surface layer units of Mars, ultimate bearing capacity, dynamic penetration resistance, angle of critical slope stability, and rover traffiability for those units will be determined. The objective of the investigation is to provide the geotechnical design parameters necessary for lander and rover development and the information necessary to assess landing site hazards.

Several methods for determination of dynamic penetration resistance including closed form solutions by Halajian and Reichman (1969) and more recent finite element analysis by Chua, Johnson, and Galloway, (2000) will be used. Effects of Mars gravity and low atmospheric pressure on dynamic penetration resistance will be taken into account (Perko and Nelson, 2000).

At present, it is unlikely that future landing sites will be selected near areas of potential landslide risk due to the hazards of landing on sloped surfaces. However, future rover missions are planned with sufficiently long traverse distances that the ability to identify and avoid areas with potential landslide risk will become important. The angle of critical slope stability will be determined for different soil units on Mars using the shear strength determinations obtained and the Culmann Method for finite slopes as described in a previous section.
Several methods that have been developed for determining rover wheel trafficability from soil shear strength will be compared. One method developed for lunar exploration by Mitchell et al. (1973) allows for the determination of track depth. Another method developed more recently for Mars exploration by Moore et al. (1999) relates soil shear strength with wheel torque. The latter method can be used to estimate slipping and digging hazards on slopes.

Discussion
Current quantitative knowledge of Mars soil mechanical properties is limited to Viking and Pathfinder landing sites. Soil mechanical properties have been determined at these sites based on various methods including spacecraft footpad penetrations, surface sampler trench wall stability, miniature slope failures, and Sojourner wheel excavation effort (Moore et al., 1999). Remote sensing observations have shown that significant variability in soil composition and subsurface profile exists across the surface of Mars. Viking and Pathfinder landing sites were all within moderately rocky terrain located near the equator of Mars. The surface materials at these landing sites represent only a small portion of the various surface layers present on Mars and are not representative of the whole planet (Christensen and Moore, 1992 and Jakosky and Golombek, 2001). The upcoming rover, sample return, and human missions to Mars likely will experience terrain that differs considerably from Viking and Pathfinder landing sites. The bearing strength and penetration resistance of Mars soils need to be further evaluated by a soil engineer (Greeley, 1991). Using the highest quality remote sensing data available to date (i.e. Mars Global Surveyor photographic and laser altimeter measurements), the mechanical properties of soils in different regions of Mars are being determined. Shear strength, ultimate bearing capacity, dynamic penetration resistance, and rover trafficability are being calculated.

Conclusions
Results from the current research are relevant to all future Mars missions in that they will increase future mission success. Mars soil mechanical properties must be understood and quantified in order to design landers, rovers, sampling devices, and other equipment for future exploratory missions to the surface of Mars. It is important to be able to define the bearing capacity, risk of landslides, and risks associated with soil deformations at future landing sites. It is also important to further demonstrate techniques for determining soil mechanical properties from remote sensing data so that these techniques can be used more reliably on other planetary science missions.

References


