Unsaturated soils on Mars and their impact on human missions and settlement on Mars

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ABSTRACT

Significant recent attention has been garnered by research related to the mechanics of unsaturated soils in the geoscience, geotechnical engineering, and agricultural science. Unsaturated soils are widely distributed in semi-arid and arid regions of the world. The planet Mars, like Earth, is covered with soil originating from erosion and weathering of igneous rocks. The presence of unsaturated soils from recordings of Mars orbiters and landers are discussed in this paper. The importance of these soils and the possible geohazards that they may pose for future human exploration or colonization of Mars are presented too. In conclusion, unsaturated soils appear to exist on a large scale on Mars and can contribute to geotechnical problems similar to those on Earth. We will discover valuable information about the potential problems, and hence possible solutions, for planning human activities on Mars in future.

KEYWORDS: Mars, unsaturated soils, suction, duricrust, debris flow, collapsible soils, geotechnical hazards, human settlement

INTRODUCTION

There are plans by different authorities to have humans on Mars for exploration purposes and also for possible settlement. Main ongoing projects with regards to these plans are the Mars One project and a new proposal from NASA (1, 2).There are however several geotechnical engineering challenges that have to be addressed for success of the proposed future human projects on Mars. Geotechnical problems associated with soils on Earth located above the ground water table, (i.e. vadose zone) with negative pore-water pressure (i.e. suction) values are typically addressed using the mechanics of unsaturated soils. Most of the soils on the surface of Mars are composed of fine particles size (range of < 0.002 mm- 0.075 mm, which typically constitute clay and silts). These particle sizes are significantly influenced by the impact of low gravity (1/3 the gravity of Earth) on the Mars soil mass. Microgravity can cause difficulties in the transport mechanism of liquid water, gases, and heat inside the Martian soil (3). The soil suction is a key factor that contributes to the stability of the unsaturated soil slopes (4, 5). The mechanical properties such as the shear strength, stiffness, and bearing capacity are relatively high and offer resistance to deformation in unsaturated soils due to the contribution of suction (6-8). However, some unsaturated soils collapse (i.e. collapsible soils) or swell (i.e. expansive soils) by wetting, due to loss of suction. The soil suction potential considerably increases when temperatures fall below the freezing point of water (9). Mechanics of unsaturated soils, which is an emerging research field, has provided solutions for addressing several geotechnical problems (10). Present knowledge of unsaturated soils can be a valuable tool on Mars to facilitate future human exploration and settlement.

A SUMMARY ABOUT MARS ENVIRONMENT

There are some similarities and differences with respect to the influence of atmosphere, temperature, pressure, water and wind on the soil properties of Mars and Earth. Temperatures on Mars vary from -153 to 20 degrees Celsius in different seasons based on the location. The average temperature can vary between -50 to 0 degrees Celsius in mid-latitudes (11). Temperature ranges between -143 to -23 degrees Celsius with an average of -33 degrees Celsius have been recorded on Mars surface (12). CO2 atmosphere (Table 1) with low thickness cannot retain Martian solar heating during the day time. Average atmospheric pressure of 700-750 Pascal (7-7.5 millibars) have been recorded on Mars compared to 101.30 kPa (1,013 millibars) on Earth (11, 12). Under these low temperature and pressure values, water can hardly exist in liquid form, and will sublimate or freeze to other phases (12). There are five locations on Mars, where water may exist in liquid form under pressure and temperature for 37-70 Martian days (sols) (13). They are located between 0° and 30°N in Amazonis, Arabia, and Elysium Planitiae, and in the Hellas and Argyre impact crater (13). Pressure and temperature variation of Mars atmosphere, due to solar heating, create winds to balance these gradients (12). Existence of wind on the surface of Mars can be inferred from different forms of sand dunes on Martian surface (Fig. 1a). Presence of winds in the form of dust devils (12) has been recorded by Spirit's navigational camera (Fig. 1b).

Table 1: List of some major constituents of Martian atmosphere (11, 12).

Main chemical composition	Volume in total (%) or ppm
Carbon dioxide (CO2)	95.32%
Nitrogen (N2)	2.70%
Argon (Ar)	1.60%
Oxygen (O2)	0.13%
Carbon monoxide (CO)	0.08%
Water vapor(H2O)	210 ppm

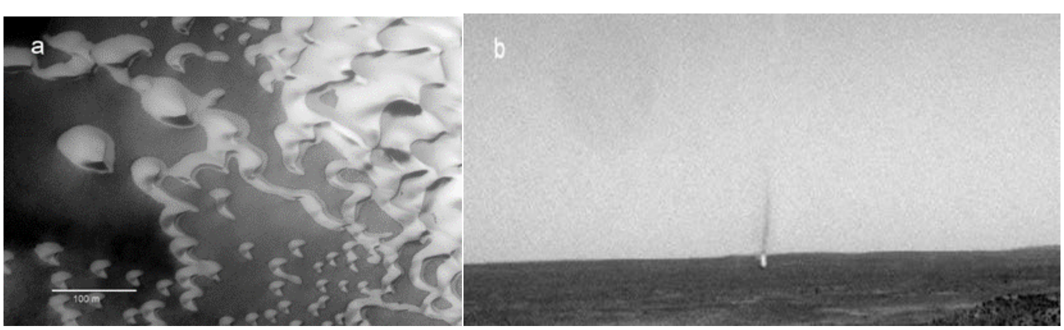

Figure 1: Wind act on Mars (a) Sand dunes (Barchans type), source: NASA/JPL/University of Arizona (b) Dust devil depicted in Spirit's camera (Image source: NASA/JPL-Caltech).

Martian soil contains a high concentration of Fe, S, and Cl elements; its red color is attributed to iron-oxides produced from weathering of rocks in wet and humid times of Mars. Some physical and engineering properties of Martian soils are summarized in Table 2 (12).

Table 2: Martian soil physical and engineering properties at three rover exploration sites

Soil properties	Mars Path Finder (14)	Spirit Mars Rover (15)	Opportunity Mars Rover (16)
Friction angle	30°–40°	~20°	~20°
Soil bearing strength		5–200 kPa	~80 kPa
Cohesion	0–0.42 kPa	~1–15 kPa	~1–5 kPa
Angle of repose	32.4°–38.3°	up to 65°	>30°
Soil bulk density	1285–581 kg m^{-3}	1200–1500kg m^{-3}	~1300kg m^{-3}
Grind energy density		11–166 Jmm^{-3}	0.45–7.3 Jmm^{-3}

DURICRUST, AN UNSATURATED SOIL ON MARS

Cemented and collapsible soils, also known as duricrust or false pebbles, exist on 25% of the surface of Mars (Figure 2). Their composition includes particles cemented by bonding agents, which has been inferred from albedo and thermal inertia parameters. They also were observed in Viking and Pathfinder landing sites (17-20). There is not much information about depth of soil layer from all parts of Mars and this applies to Earth as well. The existence of unsaturated soils on Mars in the form of false pebbles can be seen in Figure 2a. Disturbance of unsaturated cemented soils (duricrust) structure by Mars rover is seen in Figure 2b. Existence of unsaturated soils on Mars surface can be also inferred from Figure 2c-d.

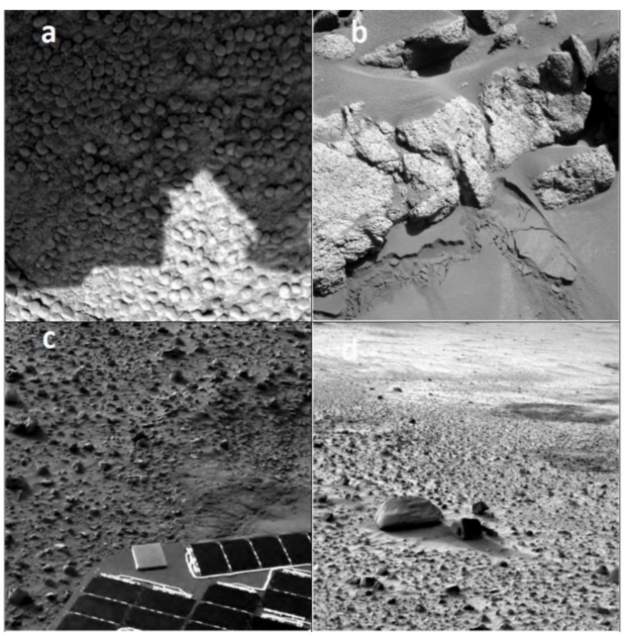

Figure 2: Presence of a cemented and collapsible soil on the surface of Mars in unsaturated conditions. a) False pebbles on Mars observed by Spirit Mars rover at Gusev Crater-- (Image source: NASA/JPL/Cornell/USGS). b) Unsaturated soil (Duricrust) on the slope near Gusev Crater collapsed by Spirit Mars rover movement (Image source:

NASA/JPL/Cornell). c & d) Distribution of unsaturated soils on the Mars surface as depicted by panoramic camera of Spirit Mars rover near Gusev Crater (Image source: NASA/JPL/Cornell).

Presence of a vadose zone or unsaturated zone at the subsurface of Mars can be inferred from sedimentary assemblies such as fans, deltas and cross-bedded layer (21-23). Suction and minimization of surface tension between soil particles contact trigger precipitation of minerals. Deposition of new crystals happens in transient mode to the unsaturated phase between soil grains from pore water with high concentration of chemicals (24). The key geotechnical problem related to unsaturated soils can arise from the collapsing nature of duricrust on Mars. The surface of Mars is dotted with false pebbles, which are gently cemented fine-grained soils that are with silt sizes. They were crumbled when the Viking sampler arm was picking them up. The collapsible soil in dry status has considerable stiffness but collapses rapidly when it is saturated with water. The light cementation by salts or clay pods is dissolved by water introduction, and the soil collapses to a denser structure (9). It is likely to encounter some engineering problems if foundations are constructed on the unsaturated collapsible soils. These soils can suddenly collapse due to overloading, a sinusoidal dynamic load, or wetting due to the melted ice. Some solutions can be applied to avoid the hazards associated with the collapsible unsaturated soils in future human settlement. First, this type of soil can be removed from places where their thickness is low. Second, the soil can be compacted to a higher density to achieve favorable conditions. These solutions are suggested based on the following assumptions: two types of structures that include either surface or underground shelters can be built on Mars to protect humans against harsh weather conditions or intensive solar radiation impact. For any structure built on the Mars ground or underground surface within thick deposits, geotechnical properties of the soil should satisfy the minimum requirements with respect to stability and deformation (i.e. collapse).

DESICCATED POLYGONS AND UNSATURATED PHASE

Abundant polygonal cracks (Figure 3 and 4) can be observed on the surface of Mars from images sent by lander and orbiting spacecrafts (25-27). These polygons on Mars have different sizes ranging from 2 to 3 m up to 10 km in diameter. Thermal contraction, desiccation, or volcanic processes are the main factors for small size polygons (2 to 20 m). Intermediate size (20–300 m) formation and tectonic activities are responsible for the larger, kilometer sized, polygons (27-33). The desiccation theory suggests that endogenic lakes or the saturated sediments formed inside the impact craters contributed to polygon type soil structure (27). It was suggested that those lakes possibly contain water, saturated by the hydrothermal processes (34) or by the impact induced groundwater leakage just after the impact event. Desiccation is a drying phase associated with evaporation of water from the surface or due to diffusion processes that occur in a soil which was originally in a saturated state. These visible processes suggest movement of the liquid water due to water potential difference. Such a process can be attributed to vapor movement as a result of variation in the water vapor pressure. If the soil is prevented from the contraction due to the loss of volatiles, stress accumulates and reaches a value that is more than the strength of the soil. As a result, cracks form to release the excess stress (27). The phenomenon associated with the desiccation cracks in clay soils on Earth is similar as per the studies by different researchers (35-41).

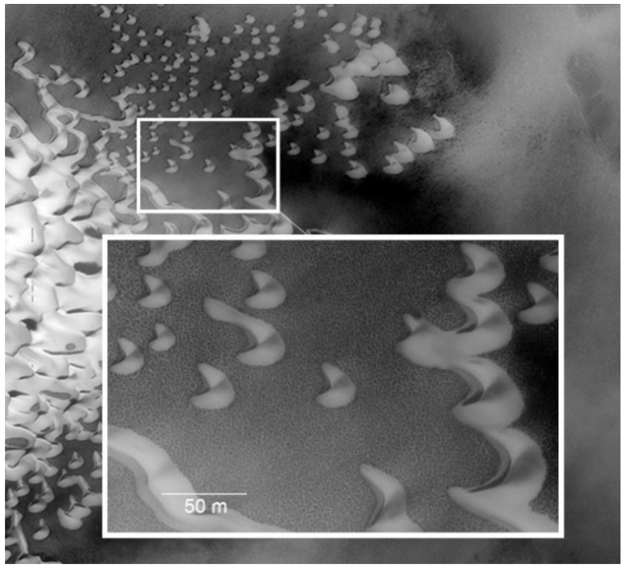

Figure 3: Desiccated polygons, visible near to Martian dunes, depicted by high resolution HiRISE camera installed on the Mars Reconnaissance Orbiter (Image PSP_008165_2505, source: NASA/JPL/University of Arizona)

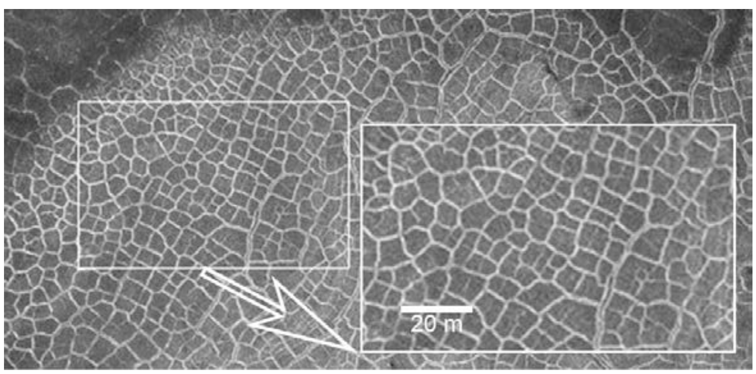

Figure 4: Desiccated polygons filled with ice, depicted by high resolution HiRISE camera (Image: PSP_007372_2475, source: NASA/JPL/University of Arizona)

LANDSLIDES AND ROLE OF UNSATURATED SOILS

Debris flows and gully landforms can be seen commonly on the Martian surface (21). Cross-cutting interaction with other surficial features on Mars and coverage by the young age dunes means that these gullies are comparatively juvenile features. Additionally, the gullies have sharp manifestation in contrast to the older features that were influenced by landslides or aeolian processes. Concentration of gullies occurs along some latitudes with more exposure to the Sun. Research was performed by (42) on the amount of exposure to solar radiation in the Martian hillslopes in the northern hemisphere, both with gullies and no gullies. It was observed that slopes with gullies have a comparatively steady amount of exposure to the Sun during the year. This exposure was because of their slope geometries, and particularly due to their latitudes and aspects (facing direction). Gullies formation indicates that there are unsaturated soils in these regions which experience wetting phenomena. The wetting of unsaturated soils can be attributed to ice melt and capillary movement of water. The water saturates surficial soils, reduces suction and decreases the shear strength, leading to their downward movement (i.e. collapse). Consequently, debris flows, gullies and fan-shape features are created on the surface of Mars (Figure 5-Left). Landslides can have different triggering mechanisms and discussion on this topic is not provided due to space limitations of the paper. Landslides in small or massive scale (Figure 5) in the past or present time of Mars can be due to wetting path or due to saturation phase in the unsaturated soils in addition to the influence of gravity and dynamic loads. Dynamic loads can originate from induced seismic effects of meteorite impacts (Figure 5-Right) or Marsquakes. Presence of collapsible soils in unsaturated phase with potential of shear strength loss due to dynamic loading is a major factor for landslide occurrence on Mars. Also, debris flow due to the wetting or saturation of the unsaturated soils is main type of dominant landslide mechanism on the surface of Mars. An investigation showed that liquid flow in the shallow subsurface, the slope gradient, and stability of regolith mantle on the slope can control debris flows on Mars (43). Based on the previous research and recent results (43) from SHARAD (Shallow Radar Mars Reconnaissance Orbiter), it can be deduced that a liquid material will cause wetting phenomena in Martian unsaturated soils. This liquid is likely the groundwater originating from either the water-ice in the Martian subsurface, the melt of vastly distributed shallow subsurface ice or from subsurface hydrothermal activity. In future, locations of human settlement on Mars close to elevated areas, dormant volcanoes and slopes should be avoided. This is to alleviate gravity impact, dynamic loads, and wetting of the unsaturated soils by ice melt that can trigger landslides, including fast moving debris flows. Water exists in mixture with ice or only in ice form under Martian surface. Exposure to solar energy, underground hydrothermal circulation and diffusion of water vapor to surface or meteorite impact shocks, provide heat sources for melting ice. These heat sources can melt the ice undersurface and create liquid water. Water can percolate inside the soil or rise by capillary movement, reducing suction of unsaturated soils, contributing to shear strength reduction and increase in deformation (i.e. collapse), as a result.

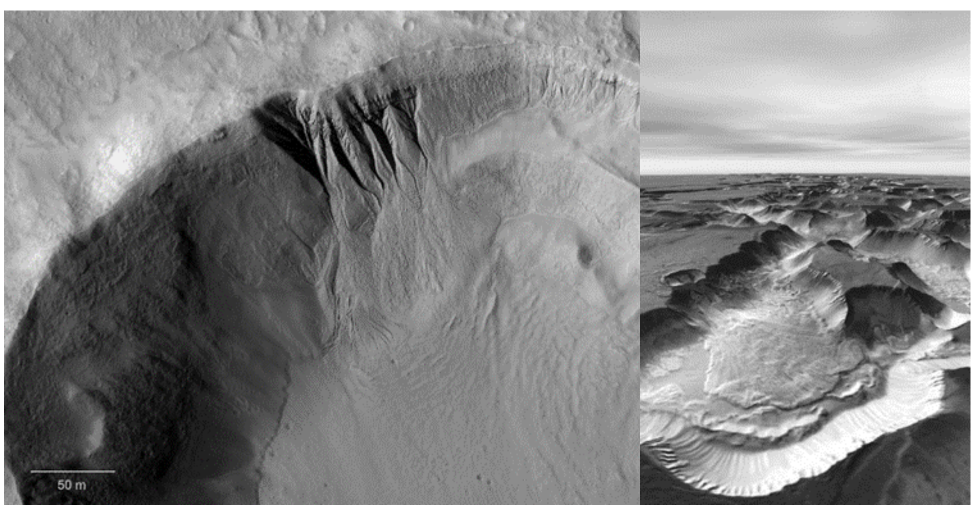

Figure 5: Left) Debris flow and gullies in a southern hemisphere crater on Mars depicted by HiRISE camera, and their formation by thermal and the unsaturated soils influence (Left Image: PSP_003162_1445, Image source: NASA/JPL/University of Arizona). Right) a landslide on Mars surface triggered by meteorite impact and collapsing nature of unsaturated soils due to dynamic load. (Image from thermal emission imaging system, THEMIS, in thevast Noctis Labyrinthus system, located west of the giant rift valley of Vallis Marineris;-

Image source: NASA/JPL/University of Arizona; Color changed to gray scale for publication purpose).

THE FROZEN SOIL IN UNSATURATED STATUS

Frozen soils exist on a vast surface area of Mars. Temperature on Mars may vary from -153 to +20 degrees Celsius in different locations and times of year. Heat from exposure to sunlight, underground hydrothermal gradient, and from meteorite impact shock can change environmental conditions and melt frozen soils. The soil mechanical properties; namely, stiffness and shear strength are key parameters required for the design in foundations. Frozen soils exhibit higher initial tangent modulus (i.e. stiffness) because of resistance produced within the soil by ice, which intensifies by increase in confining pressure. In the silts, which are mostly fine-grained cohesionless soils, the soil suction enhances the apparent cohesion and in turn increases the shear strength. Knowing that the soil suction increases in the frozen soils, it can be implied that moisture content controls the shear strength of the soil through the contribution arising from suction (9). Problems arise when the saturation degree of the soil increases due to melting of ice. Due to this reason, there is a reduction in soil suction, shearing strength, stifness and bearing capacity of thawed soil. The heat source can be from exposure to the Sun or hydrothermal systems.

CONCLUSIONS

Unsaturated soils in future exploration and settlement

It can be inferred and concluded from this research that unsaturated soils exist on a large scale on Mars. We should expect that these soils will pose some geotechnical problems for future human exploration or settlement. The main evidence, as explained in this paper that supports the vast presence of unsaturated soils on the surface of Mars, can be attributed to duricrust. Duricrust, a lightly cemented unsaturated soil that is collapsible in nature, covers most parts of the surface of Mars. It was presented that the unsaturated soils (duricrust) can likely contribute to geotechnical problems. Problems such as sudden settlement due to collapsible nature of duricrust and slope failure can likely occur on Mars. Reduction of stiffness, shear strength and bearing capacity can be induced by the wetting phenomena in the unsaturated soils. The wetting water can originate from ice melt due to exposure to Sun or contact with the underground volcanic hydrothermal systems. More research is recommended on the interactions of water, water-ice, dry ice, and soil considering the influence of soil suction on the hydraulic and mechanical properties of the unsaturated soils. Other recommendations include experiments in the space missions with respect to the influence of microgravity using different types of martian simulant soils mixed with water or dry ice. These tests will allow us to gain knowledge about the influence of the soil suction on the geotechnical properties that can be useful for civil and mechanical infrastructure design on Mars. Finally, research and investigation on the unsaturated Martian soils should continue to better understand problems, and to propose valid solutions. Such studies can contribute to successful human exploration and settlement on Mars in the near future..

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