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SOIL MECHANICS ON THE MOON, MARS, AND MULBERRY; W.D. Carrier, III, Bromwell & Carrier, Inc., Lakeland, Florida

From a soil mechanics point of view, the Moon is a relatively simple place. Without any water, organics, or clay minerals, the geotechnical properties of the lunar soil are confined to a fairly limited range. Furthermore, the major soil-forming agent is meteorite impact, which breaks the big particles into little particles; and simultaneously, cements the little particles back together again with molten glass. After about a hundred million years of exposure to meteorite impact, the distribution of particle sizes in the soil achieves a sort of steady state. The majority of the returned lunar soil samples have been found to be well-graded silty-sand to sandy-silt (SM in the Unified Soil Classification System). Each of the particle size distributions plots within a relatively narrow band, which appears to be uniform over the entire lunar surface. This further restricts the range of physical properties of the lunar surface.

The most important factor affecting the behavior of the lunar soil is its relative density; i.e., how tightly the individual particles are packed together. Relative density, D_R, is defined as:

$$D_R = \frac{\rho_{max}}{\rho} \times \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \times 100\%,$$

where ρ is the density of the soil as-deposited; ρ_{min} is the minimum possible density (i.e., as loose as the soil can be placed); and ρ_{max} is the maximum possible density (i.e., as dense as it can be packed). If $\rho = \rho_{min}$, $D_R = 0\%$ (very loose) and if $\rho = \rho_{max}$, $D_R = 100\%$ (very dense). The meteorite impacts loosen and stir the surface, but just a few centimetres down, the shock waves shake and densify the soil. Right at the surface, the soil is loose, with a relative density of about 30%. Ten to twenty centimetres deep, the soil is dense to very dense, with a relative density of 80% to more than 90%. The density of the sub-soil is much greater than can be accounted for by the weight of the over-lying soil. The relative density is greater, in fact, than can be achieved on Earth with heavy construction equipment. Consequently, the geotechnical properties of the lunar soil are relatively uniform and very safe with respect to bearing capacity, settlement, and trafficability. This was one of the most important geotechnical findings from the Apollo program and was deduced from penetrometer tests performed <u>in situ</u> and from laboratory tests performed on returned lunar samples.

In contrast, martian soils should exhibit an extremely wide range of properties. We already know that there is a small amount of water in the soil, greater than in the martian atmosphere. Furthermore, the soil is suspected to be smectitic clay. That makes two out of the three factors that greatly affect the properties of terrestrial soils (we do not believe, yet, that there are significant organics in the martian soil). Acted upon by wind and sun, the martian soil could range from a light fluff to a hard brick. Furthermore, desiccation cracks could occur in the clay with a width of one to two metres and depth of 10 metres or more. These cracks could be covered with loose soil and could represent a hazard similar to crevasses in a glacier. On the positive side, there could be large quantities of water trapped in the pores of the clay with could be mined (but not pumped). There may even be a groundwater table.

It is essential that certain tests be performed as soon as a sample is taken on the martian surface. These include: moisture content, pH, and cation and anion concentrations. Each sample must be carefully sealed for earth-return, otherwise, chemical reactions could occur which could alter its properties. It is also very important that penetrometer measurements be made on a systematic basis. For example, Lunokhods I and II conducted more than one thousand penetrometer tests over a combined traverse of 47 kilometres on the Moon. These tests provide a simple, rapid method of evaluating the condition of the soil, and for discriminating among different soil types and deciding which samples to collect.

A terrestrial analogue for the martian soils occurs in the region around the small town of Mulberry in central Florida. This is the center of phosphate mining in the U.S. A by-product of the ore-beneficiation process is a very plastic, smectitic clay. The phosphate industry produces approximately 36 million dry tonnes of clay each year. The clay is deposited hydraulically as a dilute slurry into large holding ponds, in many cases, deeper than 20 m. More than 40,000 hectares of clay ponds presently exist and about 1500 new hectares are created annually.

When a clay pond is reclaimed, the groundwater table is lowered as much as 10 m below the clay surface. The clay volume shrinks about 40% and an extensive network of cracks forms over the surface. The physical properties of the clay undergo enormous changes as the clay dries out. Of course, the moisture content in a reclaimed clay pond is much greater than is presently found in martian soil. Nonetheless, the pond represents an early stage in the development of the martian surface. In order to understand the present condition of the martian surface, it is essential to study its early formation. To know Mars, you must come to Mulberry, and I invite my geology and soil physics colleagues to visit us there.