

MECHANICAL PROPERTIES OF LUNAR SOIL: DENSITY, COHESION, AND ANGLE OF INTERNAL FRICTION

J. K. Mitchell, Univ. of Calif., Berkeley, Calif.; R. F. Scott, Calif. Inst. of Technology, Pasadena, Calif.; W. N. Houston, Univ. of Calif., Berkeley, Calif.; N. C. Costes, Marshall Space Flight Center, Huntsville, Ala.; W. D. Carrier, III, Manned Spacecraft Center, Houston, Texas; and L. G. Bromwell, Mass. Inst. of Technology, Cambridge, Mass.

Knowledge of the mechanical properties of lunar soil has been accumulating since well before the first lunar landings. With continued exploration, however, it has been possible to decrease the degree of speculation and to increase the certainty with which these properties and their variability are known. Of particular importance and interest to lunar science are density (ρ), cohesion (c), and angle of internal friction (ϕ). Knowledge of c and ϕ are important, both because individually they reflect density, composition, and environmental influences, and because together they control the soil strength. The soil strength, in turn, dictates the maximum possible soil slope angles, the bearing capacity of the surface, and the resistance to penetration of objects into the soil.

The gradation of the lunar soil (silty fine sand with particles generally in the range of about 0.01 mm to 5 mm) is such that density and porosity are the most important characteristics controlling the physical behavior. For terrestrial soils of similar gradation it has been well established that the cohesion, the friction angle, the compressibility, and the modulus of deformation may all vary significantly for relatively small changes in density. Evidence to date indicates that the lunar soil behaves in a similar manner. Density and porosity are of importance also to those investigators concerned with seismic wave propagation, thermal conductivity, and cosmic rays. Substantial regional and local density variations and changes in density with depth have now been observed. The development of suitable explanations for these variations will be of importance in the understanding of lunar history.

A variety of methods has been used for estimating lunar soil density, cohesion and friction angle. In this paper a number of these methods are cited and the results noted in an attempt to develop a historical perspective on each of the three properties. Conclusions are drawn relative to the ranges of values and the reliability with which they are known based on data available through Apollo 15.

Density

Early density estimates of as low as 0.3 gm/cm^3 up to 3 gm/cm^3 were based

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largely on assumption and deduction from earth-based optical, thermal and radar measurements. First in-place density measurements were by a gamma ray device on the Soviet Luna XIII. Grain-size distribution and footpad-surface interaction as well as the results of the Soil Mechanics Surface Sampler experiment were used to obtain a density estimate of 1.5 gm/cm^3 in the Surveyor Program.

A rotary drill sample returned by Luna XVI yielded a density of 1.2 gm/cm^3 . Core tube sample data have provided the best density data during the Apollo program, although additional density estimates have been possible using the results of studies on lunar soil simulants. The best available data indicate densities in the range of about 1.3 to 2.1 gm/cm^3 . Such a range can be expected to embrace a wide spectrum of strength and compressibility behavior.

Cohesion

Cohesion estimates prior to the Apollo program were derived mainly from television observations, landing leg strain gage data, and the Soil Mechanics Surface Sampler during the Surveyor program. Best estimates were in the range of 0.3 to 0.7 kN/m^2 (0.05 to 0.10 psi). During Apollo cohesion evaluations have been possible on the basis of (1) analysis of blowing dust during LM descent, (2) failure of the soil mechanics trench wall, (3) penetration resistance measurements, and (4) simulation studies. Values as low as 0.03 kN/m^2 (0.005 psi) and as high as 1.0 kN/m^2 (0.15 psi) have been obtained, with the highest values associated with the finest grain sizes and highest densities.

Angle of Internal Friction

Pre-Apollo estimates of friction angle were based on analyses of slope angles (Ranger and Orbiter programs) footpad and Soil Mechanics Surface Sampler interactions with the lunar surface (Surveyor program), and boulder track records (Orbiter). Values from 10° to 55° were indicated from these results, although 35° to 40° appeared the best estimates. During Apollo the friction angle has been deduced from (1) penetration test data, (2) simulation studies, and (3) MET track (Apollo 14) data. It now appears that values as high as 50° are possible for the soil in a dense packing. The lower bound, which would be associated with the soil in its loosest state, is still undetermined.