

## Cone penetration resistance test—an approach to evaluating in-place strength and packing characteristics of lunar soils

N. C. COSTES

National Aeronautics and Space Administration,  
G. C. Marshall Space Flight Center, Huntsville, Alabama 35812

G. T. COHRON

Cohron Industries, Inc., Huntsville, Alabama

and

D. C. MOSS

National Aeronautics and Space Administration,  
G. C. Marshall Space Flight Center, Huntsville, Alabama 35812

(Received 3 March 1971; accepted in revised form 31 March 1971)

**Abstract**—Cone penetration resistance tests on fine-grained, granular lunar soil simulants of varying grain-size distribution and consistency, performed under terrestrial gravity conditions and onboard the U.S. Air Force KC-135 aircraft during  $\frac{1}{6}g$ ,  $1g$ , and  $2g$  flight trajectories, are described. The test results indicate that the average resistance to penetration,  $\bar{q}_c$ , and its average rate of change with depth,  $G$ , of these simulants decrease monotonically with decreasing  $g$  level and are sensitive indicators of the soil dry bulk density, void ratio and relative density. It is also shown that  $\bar{q}_c$  and  $G$  can be used with bearing capacity theory to determine the in-place shear strength characteristics of the soils tested.

Based on the analytical methods developed herein and on crude soil penetration data obtained from the Apollo 11 and Apollo 12 missions, upper bound estimates of the in-place bulk density and the angle of internal friction of the lunar soil are of the order of  $1.85 \text{ g/cm}^3$  and  $45^\circ$  for the soil at the Apollo 11 site, and of the order of  $1.82 \text{ g/cm}^3$  and  $42^\circ$  for the soil at the Apollo 12 site. On the basis of measured soil bulk density values of  $1.71 \text{ g/cm}^3$  and  $1.74 \text{ g/cm}^3$ , obtained respectively from Apollo 11 and Apollo 12 core tube samples, the in-place angle of internal friction of the lunar soil at the corresponding Apollo 11 and Apollo 12 core tube sites is estimated to be  $36.8^\circ$  and  $37.7^\circ$ , and its cohesion to be of the order of  $9 \times 10^{-2} \text{ N/cm}^2$  and  $7 \times 10^{-2} \text{ N/cm}^2$ . These findings are in agreement with independent evaluations of lunar soil mechanical properties.

The functional characteristics of a portable, self-recording penetrometer design concept, which is currently being brought to flight status for use in future Apollo missions, is described.

### INTRODUCTION

BECAUSE NO SPECIAL soil mechanics testing or sampling equipment were included in the Apollo 11 and Apollo 12 missions and no force or deformation measuring devices were utilized during the surface activities, analysis of the in-place physical characteristics and mechanical properties of the lunar soil from data obtained during the LM landing or the astronaut surface extravehicular activities (EVA) has been primarily descriptive and qualitative (COSTES *et al.*, 1970; SCOTT *et al.* 1970).

To gain a better insight on the strength and deformation characteristics of the lunar soil at the Apollo landing sites, studies on the mechanical behavior of simulated lunar soils have been carried out at the MSFC Space Sciences Laboratory prior to and since the Apollo 11 and 12 missions (COSTES *et al.*, 1969; OLSON, 1969; and SMITH, 1969). Parallel studies, under contract with the MSFC, have been conducted by the University of California, Berkeley (MITCHELL *et al.*, 1969, 1970a, b) and by the USAE Waterways Experiment Station (WES), in connection with studies relating to the Lunar Roving Vehicle program (FREITAG *et al.*, 1970; GREEN and MELZER, 1970).

Parallel with these studies, considerable effort has been spent at the MSFC Space Sciences Laboratory to develop suitable instruments and techniques for measuring directly the mechanical properties of lunar soils. Developments in soil mechanics in the last 30 years have shown that penetrometer tests are proper techniques for quick determination of the sub-surface soil properties that influence the bearing capacity and settlement of foundations. The cone penetration resistance has also been used extensively as a sensitive and convenient measure of soil strength in mobility research (WES, 1945). Dimensional analysis has been introduced to derive "mobility performance numbers" (FREITAG, 1965; POWELL and GREEN, 1965) which lend themselves to the establishment of rational criteria for the design and evaluation of lunar roving vehicles based on cone penetration resistance measurements performed on the lunar surface.

The cone penetration resistance has been shown to be not only a sensitive indicator of the in-situ packing characteristics of cohesionless soils, such as their dry bulk density, void ratio and relative density (TERZAGHI and PECK, 1948), but also of the type of cohesionless soil being penetrated. Also, the mean grain size, the uniformity and the compactibility of cohesionless soils have been found to have considerable influence on the penetration resistance versus relative density relations for such materials. Extensive reviews of recent research in this field are given by SANGLERAT (1967); SCHULTZE and MUHS (1967); VESIC (1967); MELZER (1968); HVORSLEV (1970); and MELZER (1971).

In this paper, emphasis is placed upon the cone penetration resistance test, and the design characteristics of a portable, self-recording penetrometer, developed by the MSFC Space Sciences Laboratory for use during the Apollo missions, are discussed. Comparison is made between the physical characteristics and mechanical properties of the soils tested and the actual lunar soil mechanical behavior observed during the Apollo 11 and Apollo 12 EVA's and the preliminary examination of returned lunar samples at the Lunar Receiving Laboratory (LRL). From this comparison, inferences are drawn regarding the in-situ density and shear-strength characteristics of lunar soil encountered at the two Apollo landing sites.

#### APOLLO SELF-RECORDING PENETROMETER

A cone penetrometer design concept that meets the operational constraints of an Apollo manned mission is the device shown in Fig. 1, developed at the MSFC Space Sciences Laboratory. The instrument attaches to the Apollo Lunar Hand Tool (ALHT) Extension Handle to conserve weight and space. As shown in Fig. 1, it

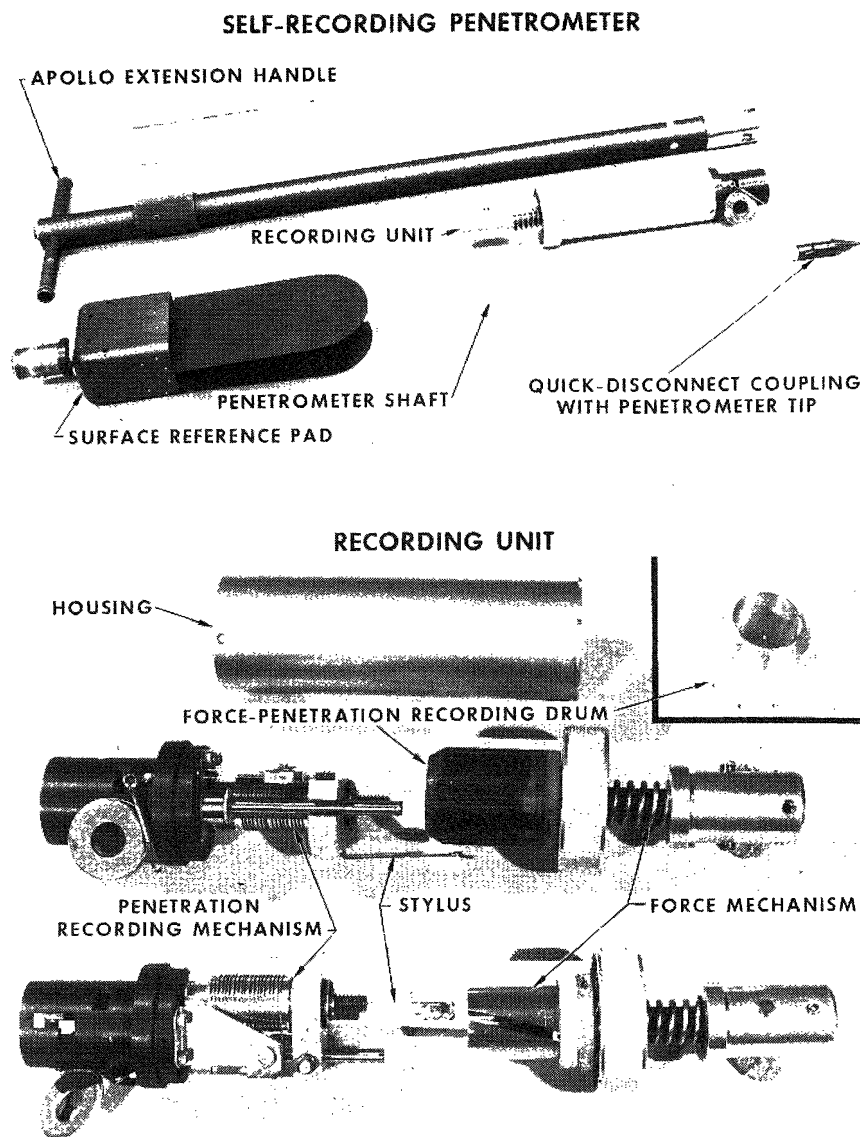


Fig. 1. Self-recording penetrometer developed at the MSFC Space Sciences Laboratory for use on the lunar surface during Apollo missions. Overall length, excluding ALHT extension handle: 114 cm (45 in.). Weight: 8.9 N (2 lbs). Maximum penetration: 76.2 cm (30 in.). Maximum force applied by spring: 111 N (25 lbs), compatible with limiting capabilities of suited astronaut in lunar gravity. Weight of recording drum: 0.28 N (1 oz).

consists of three assemblies: (1) a recording unit; (2) a penetrometer shaft with replaceable penetrating elements (tips); and (3) a surface reference pad.

Through the cable mechanism shown in Fig. 1, the relative motion between the surface reference pad and the penetrometer shaft actuates the stylus to move axially along the recording drum. A sinkage of 76.2 cm (30 in.) produces a 2.5 cm (1 in.) record. Forces are applied through the extension handle and deflect the calibrated coil spring. Axial deflection of the spring is converted to rotation of the recording drum in an amount proportional to the applied force. The maximum force that

can be applied through the spring causes a  $30^\circ$  rotation of the drum. The rotation of the drum and the axial deflection of the stylus produce a unique force-penetration diagram inscribed on the recording drum. According to this concept, only the data drums, each containing 12 or more individual force-penetration diagrams, would be returned to Earth.

This basic design concept has been endorsed by the soil mechanics team and presently is being brought to flight status by the Manned Spacecraft Center for inclusion on Apollo 15 and subsequent missions.

## CONE PENETRATION RESISTANCE TESTS ON SIMULATED LUNAR SOILS

### *Physical properties of lunar soil simulants*

In order to assess the type of scientific information that can be derived from penetration resistance data obtained from the lunar surface by a device such as the cone penetrometer described in the previous section, an extensive theoretical and experimental program has been carried out at the MSFC Space Sciences Laboratory using simulated lunar soils at various gradations and consistencies. The basic material selected for these studies has been a crushed basalt from Napa, California, having angular grains and a specific gravity of 2.89. The various gradations at which this lunar soil simulant (LSS) was mixed are shown in Fig. 2 along with grain-size distribution curves from lunar soil samples collected during the Apollo 11 and 12 missions.

In addition to the lunar soil simulation studies with the LSS, lunar roving vehicle mobility performance simulation studies prior to the Apollo 11 landing were conducted on a wind-deposited sand from the desert near Yuma, Arizona (FREITAG *et al.*, 1970).

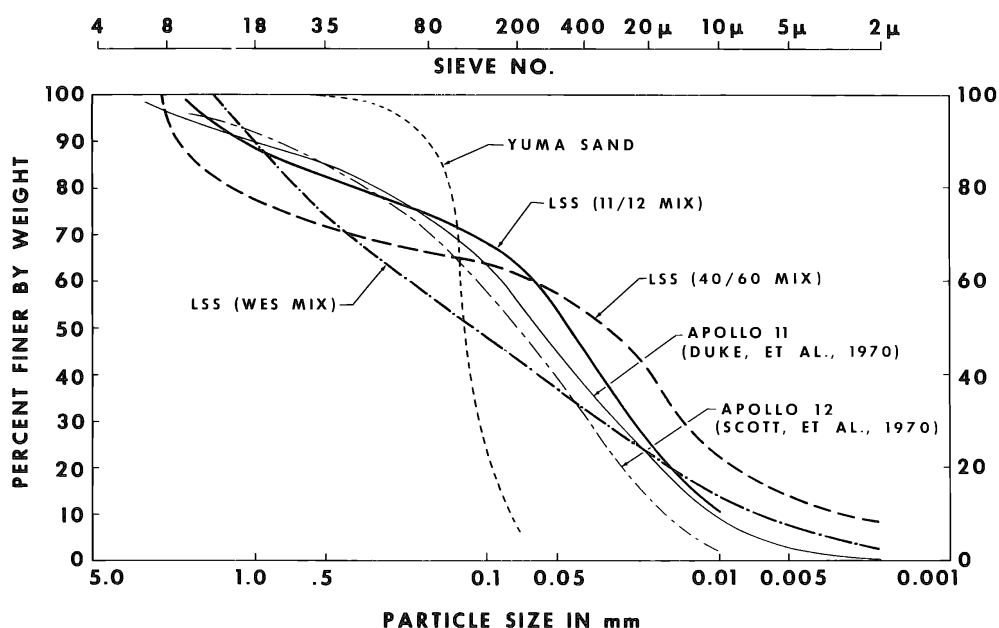


Fig. 2. Grain-size distribution characteristics of lunar soil simulants compared with gradation curves of Apollo 11 and Apollo 12 lunar soil samples.

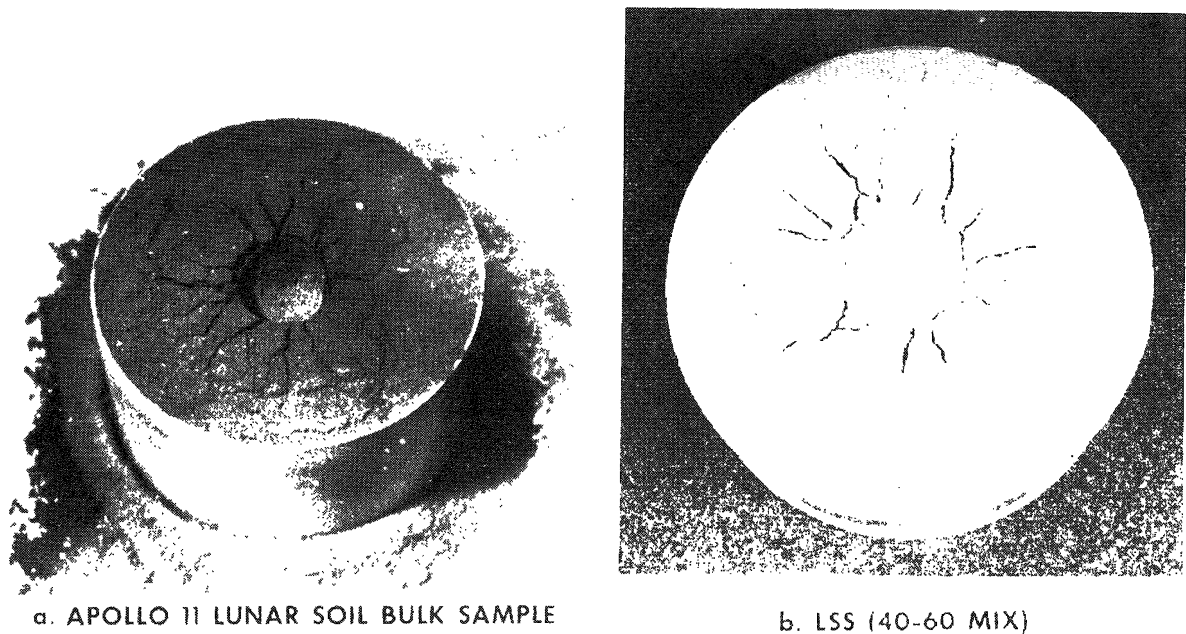


Fig. 3. Comparative analysis of penetration resistance tests on Apollo 11 lunar soil bulk sample (COSTES *et al.*, 1970) and LSS, both placed at an average void ratio of 0.7. Note mode of deformation of both samples at failure. Triaxial compression tests performed on LSS at the same void ratio verified the assumption by COSTES *et al.* (1970) that bearing capacity theory can be used with soil bulk density and penetration resistance data to determine probable range of shear strength parameters of soil tested.

The gradation of this soil is shown also in Fig. 2. In this paper, reference to this material is made only for the purpose of testing the validity of methods used in analyzing soil penetration resistance data.

The mechanical behavior of the LSS has been studied extensively under terrestrial gravity conditions with basic test variables: the soil grain-size distribution, dry bulk density, moisture content, confining pressure and testing techniques. For bulk densities ranging between  $1.50 \text{ g/cm}^3$  and  $1.80 \text{ g/cm}^3$ , the apparent cohesion and angle of internal friction of LSS (40/60 mix), placed at water contents ranging between 0.4% and 2.0%, bracket the values of the shear strength characteristics of the actual lunar soil (cohesion: of the order of  $7 \times 10^{-2} \text{ N/cm}^2$ ; friction angle: 35 deg to 39 deg in the normal pressure range of a few  $\text{N/cm}^2$ ) as deduced from soil mechanics data obtained during the Surveyor missions (SCOTT and ROBERSON, 1968).

The LSS (40/60 mix) was used in simulation studies prior to the Apollo 11 mission and has since been used extensively in predictions and comparative analyses, such as the one shown in Fig. 3, relating to the mechanical behavior of actual lunar soil encountered during the Apollo 11 and Apollo 12 missions (COSTES *et al.*, 1970; SCOTT *et al.*, 1970). Since the Apollo 12 mission, the gradation of the LSS has been modified as shown by the curve "LSS (11/12 mix)" in Fig. 2 to match more closely the grain-size distribution of returned lunar soil samples. The grain-size distribution of the lunar soil simulant used in lunar roving vehicle mobility performance studies (GREEN and MELZER, 1970) is shown in Fig. 2 by the curve "LSS (WES mix)."

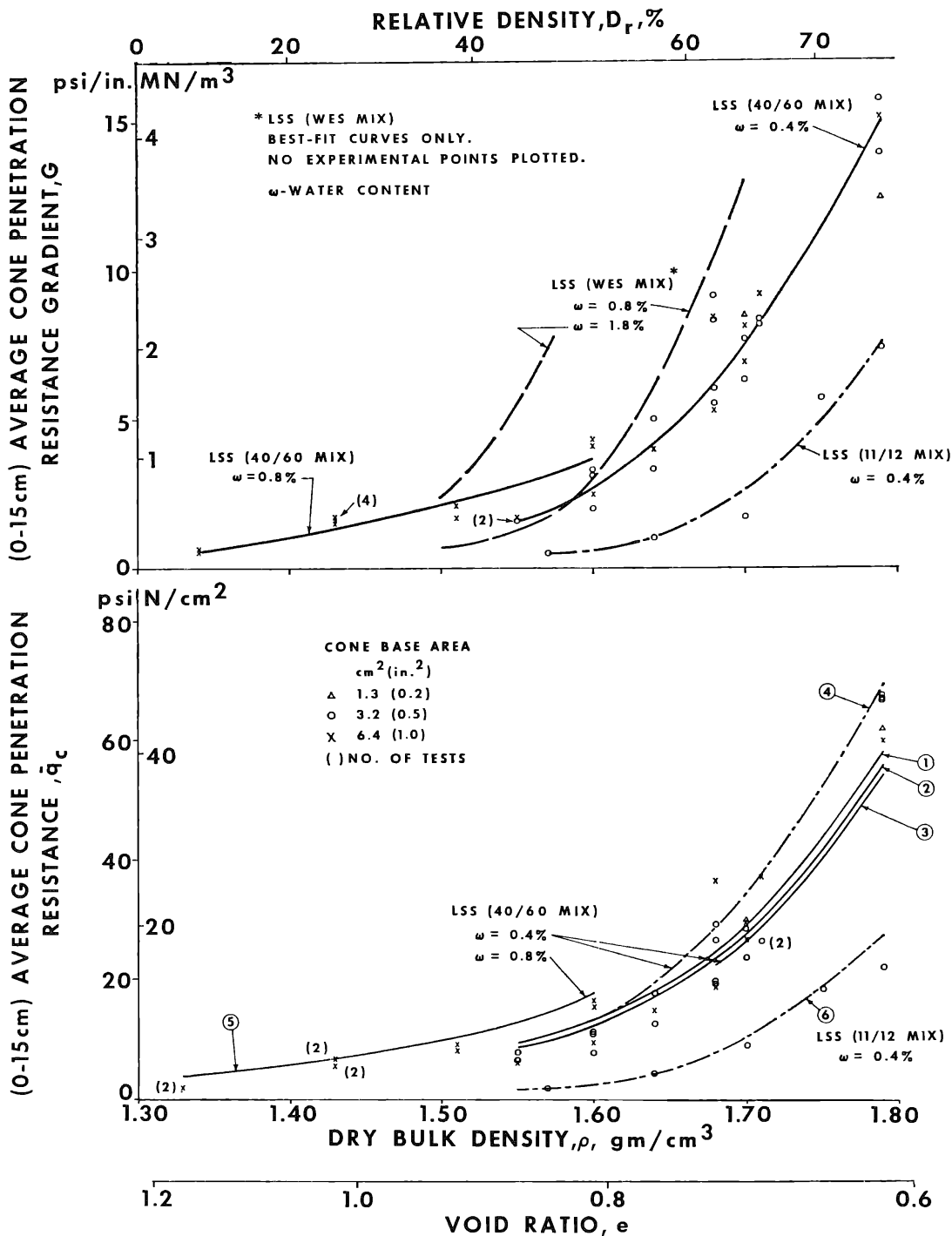


Fig. 4. Cone penetration resistance tests on LSS under terrestrial gravity conditions. (Top) (0-15 cm) average cone penetration resistance gradient,  $G$ , vs. relative density, dry bulk density and void ratio. (Bottom) Comparison of (0-15 cm) average cone penetration resistance,  $\bar{q}_c$ , data from same tests with theoretical curves computed from bearing capacity theory (MEYERHOF, 1961). Curves ①, ②, ③, and ⑤ have been computed, respectively, for cone base areas of 6.4 cm<sup>2</sup> (1.0 in.<sup>2</sup>), 3.2 cm<sup>2</sup> (0.5 in.<sup>2</sup>), 1.3 cm<sup>2</sup> (0.2 in.<sup>2</sup>), and 6.4 cm<sup>2</sup> (1.0 in.<sup>2</sup>) according to method II. Curves ④ and ⑥ have been computed for a cone base area of 3.2 cm<sup>2</sup> (0.5 in.<sup>2</sup>) according to method I.

### *Cone penetration resistance tests under 1 g conditions*

The results of cone penetration tests performed by standard equipment and according to standard procedures (Department of the Army, 1959) on LSS (40/60 mix) (SMITH, 1969), on LSS (WES mix) (GREEN and MELZER, 1970), and on LSS (11/12 mix) have been plotted in Fig. 4. As shown in Fig. 4, both the average cone penetration resistance,  $\bar{q}_c$ , and the average cone penetration resistance gradient,  $G$ , over a depth of 0 to 15 cm, of the LSS depend upon its grain-size distribution and its consistency and apparent cohesion (as indicated by its water content at a given void ratio). They are also strong functions of the packing characteristics of the material as expressed by its dry bulk density, void ratio, and relative density.

Analysis of the same data has also indicated that bearing capacity theory relating to foundations with perfectly rough conical tips (MEYERHOF, 1961) can be used to determine the in-place shear-strength characteristics of the soil, if its dry bulk density is known or can be estimated from G-versus-density or G-versus-void ratio plots.

The ultimate bearing capacity of a conical-shape foundation is given approximately by the Terzaghi equation (TERZAGHI and PECK, 1948), modified by MEYERHOF (1961),

$$q_c = cN_c + \rho g R N_\gamma + \rho g z N_q \quad (1)$$

in which  $c$  and  $\rho$  are, respectively, the cohesion and the bulk density of the soil,  $g$  is the acceleration of gravity,  $R$  is the radius of the cone base,  $z$  is the depth to the base of the cone, and  $N_c$ ,  $N_\gamma$ , and  $N_q$  are “bearing capacity factors” that depend on the angle of internal friction of the soil,  $\phi$ , the depth-cone base radius ratio,  $z/R$ , the roughness of the surface of the cone and on the cone apex angle which was 30 deg in all of the tests reported herein. In this theory, the soil is assumed to behave as an incompressible, rigid-plastic material and to fail in shear along bulb-shaped failure surfaces surrounding the cone. The traces of these surfaces on planes containing the cone axis can be described by linear segments and segments of a logarithmic spiral. Accordingly, the term “ultimate bearing capacity” refers to the applied unit load at which the shear strength of the soil mass is exceeded and the material fails in incompressible shear.

To test the applicability of equation (1) to the analysis of cone penetration resistance data, two methods were used, designated respectively as method I and method II. According to method I, the rate of change of the bearing capacity  $q_c$  with respect to depth in equation (1),

$$\frac{dq_c}{dz} = \rho g N_q, \quad (2)$$

was assumed to be equal to the average cone penetration resistance gradient,  $G$ . Accordingly, for a given cone penetration test on LSS of known density,  $N_q$  was computed from equation (2) and the indicated angle of internal friction,  $\phi_{\text{ind}}$ , of the soil was then determined from the  $N_q$  versus  $\phi$  plot for shallow, rough cones with a semi-cone angle of 15 deg (MEYERHOF, 1961). Having determined  $\phi_{\text{ind}}$ , the bearing capacity factors  $N_\gamma$  and  $N_c$  were obtained from the corresponding  $N_\gamma$  and  $N_c$  versus

$\phi$  plots appearing in MEYERHOF (1961). Finally,  $\bar{q}_c$  was calculated from equation (1) at  $z = 7.5$  cm, by entering the value of the cone base radius,  $R$ , of the instrument used, and cohesion values,  $c$ , obtained from triaxial compression and trenching tests at comparable densities (COSTES *et al.*, 1969; OLSON, 1969).

According to method II, the bearing capacity factors were determined from the  $N_c$ ,  $N_\gamma$ , and  $N_q$  versus  $\phi$  plots (MEYERHOF, 1961) by entering  $\phi$  values obtained from triaxial tests at comparable densities and the rest of the procedure was identical to that according to method I.

Comparison between values of  $\bar{q}_c$  calculated from equation (1) according to methods I and II, and experimental data on the average cone penetration resistance of the LSS mixes over a depth of 0 to 15 cm can be made in Fig. 4b. It can be seen that reasonably good agreement exists between computed and experimental data, indicating that equation (1) can satisfactorily describe the dependence of the average cone penetration resistance of the LSS on its grain-size distribution, dry bulk density, void ratio, relative density and water content which in turn govern its shear strength characteristics. Also, reasonably good agreement is indicated regarding the dependence of  $\bar{q}_c$  on the penetrometer cone size.

To test the validity of equation (1) in expressing the mechanical behavior of another material of different mineral composition, grain size and shape characteristics, and different gradation, a similar analysis was performed on data from cone penetration resistance tests conducted on Yuma Sand (Figs. 2 and 5) by MELZER (1971) and other investigators (SCHULTZE and MUHS, 1967; TURNAGE, 1971).

The results of this analysis shown in Fig. 5 again indicate very good agreement between the theoretical and the experimental results. The "theoretical curve" in Fig. 5 was calculated from equation (1) according to method I for a standard cone base area of  $3.2 \text{ cm}^2$  ( $0.5 \text{ in.}^2$ ) used in these tests.

#### *Cone penetration resistance tests under varying gravity levels*

The dependence of both  $\bar{q}_c$  and  $G$  on the gravity level, as indicated by equations (1) and (2), was checked by performing a series of cone penetration tests on LSS (11/12 mix) and Yuma Sand under varying gravity conditions, simulated onboard the U.S. Air Force KC-135 aircraft during  $\frac{1}{6}$ -g; 1-g; and 2-g parabolic flight trajectories. During these tests, vertical accelerometers located at the center of gravity of the aircraft were monitored by the pilot who controlled the  $\frac{1}{6}$ -g lunar gravity level to  $\pm 0.01 \text{ g}$ . These conditions could be produced for about 30 seconds during each "parabola," giving adequate time to perform a cone penetration test at the standard rate of 3 cm/sec (1.2 in./sec). The 2 g level during entry was controlled to within  $\pm 0.5 \text{ g}$ . However, at recovery, the g level varied between parabolas from 1.5 g to 2.5 g.

Both soil samples were placed in containers 35.6 cm by 35.6 cm in cross section and 43.2 cm deep, by sprinkling each soil from a drop height of 5 cm (2 in.). During the tests, the dry bulk density of the soils was determined from settlement measurements recorded in flight. At the top of each box, there were nine access holes (Fig. 6), spaced at 10.2 cm centers. The minimum distance between the center of the holes

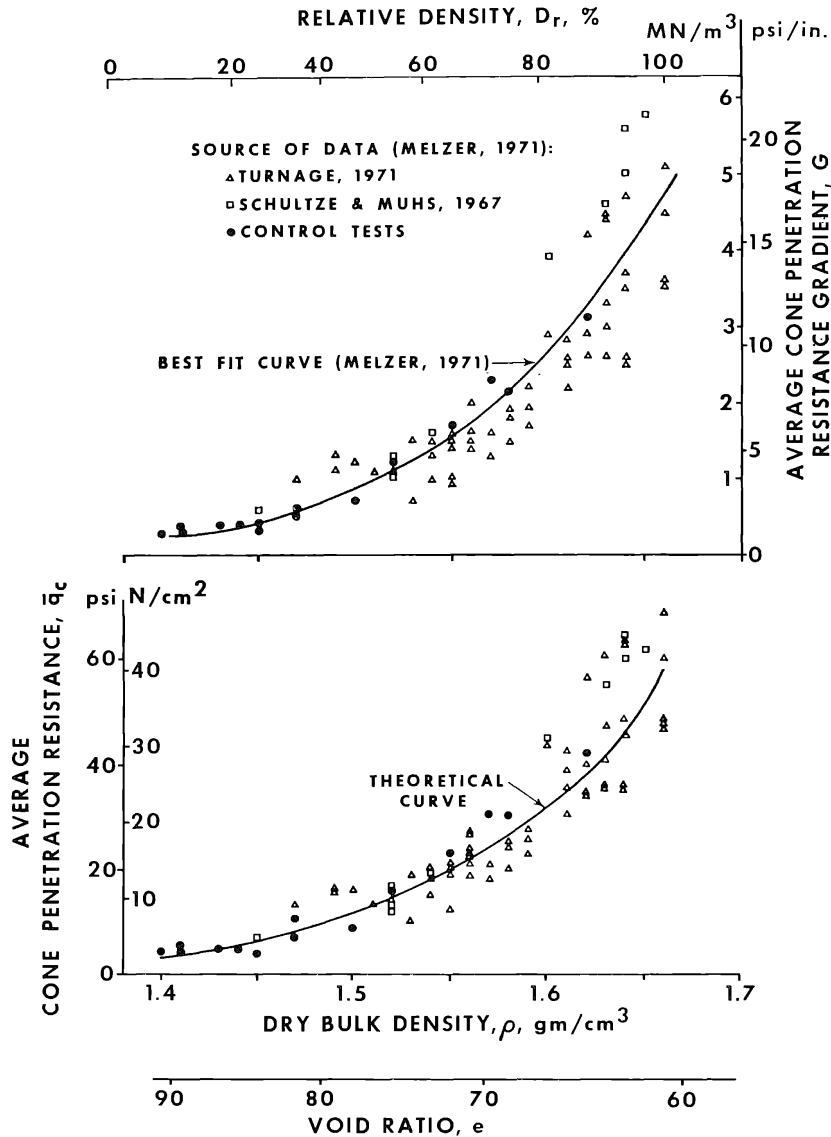


Fig. 5. Cone penetration resistance tests on Yuma Sand under terrestrial gravity conditions. (Top) (0–15 cm) average cone penetration resistance gradient,  $G$ , vs. relative density, dry bulk density, and void ratio. (Bottom) Comparison between (0–15 cm) average cone penetration resistance,  $\bar{q}_c$ , data from same tests with theoretical curve computed from bearing capacity theory (MEYERHOF, 1961) according to method I.

and the container wall was 7.6 cm. To ascertain the influence of the boundary wall and adjacent holes on the cone penetration resistance test results, for each  $g$  level there was at least one test performed at an edge hole and one at a corner hole (Fig. 6).

The apparatus for performing the cone penetration resistance tests consisted of a cone penetrometer with a standard  $30^\circ$  cone of  $3.2 \text{ cm}^2$  ( $0.5 \text{ in.}^2$ ) base area and an associated electronic system for sensing and recording the resistance to penetration of the soil at a given penetration. The overall system from force sensor to digitized force data is accurate to  $\pm 4.1\%$ . Records of depth pulses at 2.5-cm (1-in.) increments are accurate to approximately 0.1%. The results from these tests, shown in Fig. 6, indicate that inasmuch as the tests at each  $g$  level were performed during successive

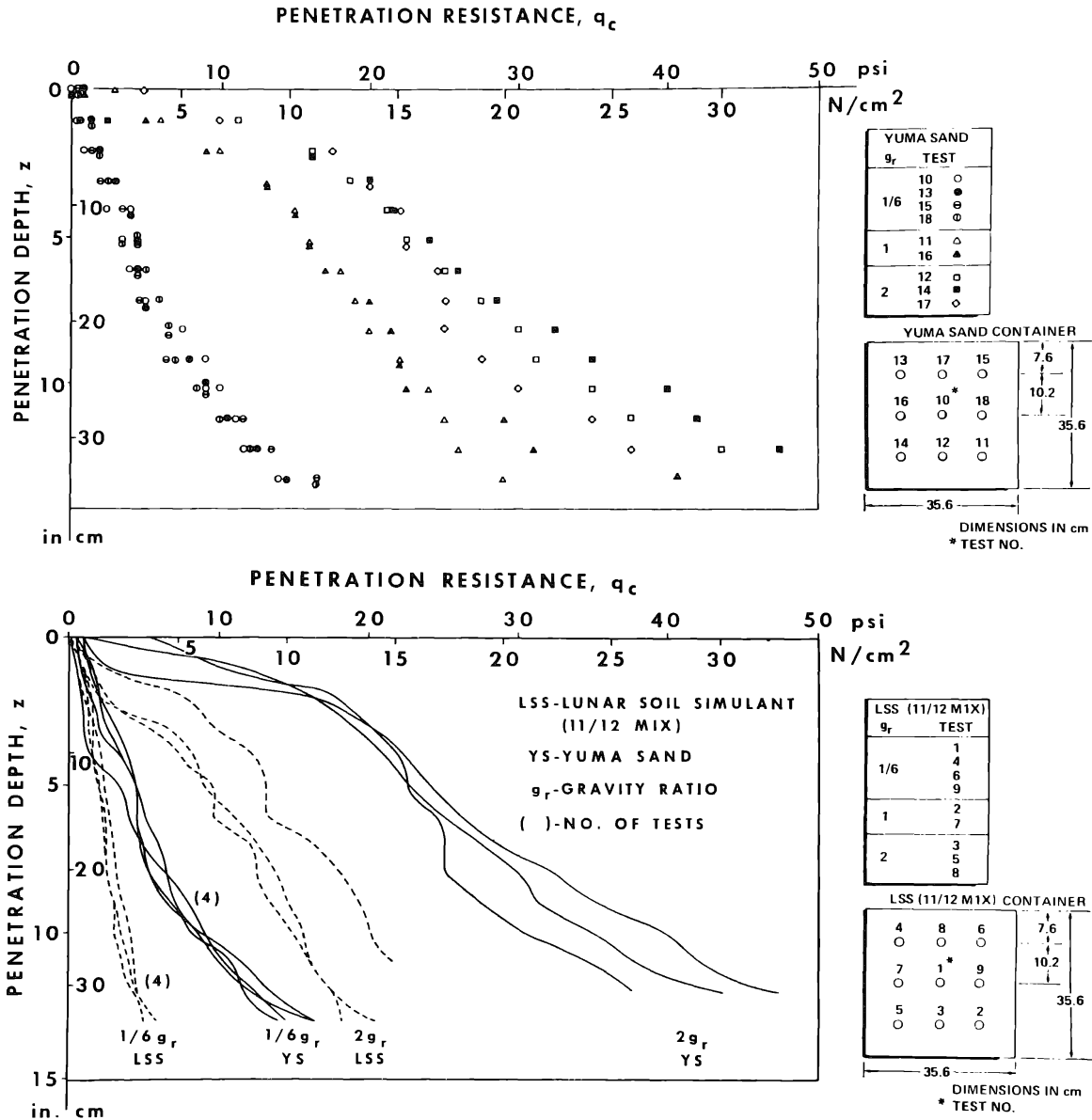


Fig. 6. Cone penetration resistance,  $q_c$ , versus penetration from tests on Yuma Sand and LSS (11/12 mix) performed under varying gravity conditions. Note effect of soil type on  $q_c$ .

parabolic flights, possible disturbances that could have occurred in either soil due to the in-flight conditions did not affect materially the test results. From the same plot, it appears also that the cone penetration resistance and its average rate of change with depth for both soils decrease with decreasing gravity level.

To test the linear dependence of the bearing capacity equation (1) on the gravity ratio  $g_r$ ,  $\bar{q}_c$  was calculated for both soils as a function of  $g_r$  using equation (1) according to method I. The  $G$  values employed in these calculations were obtained from the  $G$  versus  $g_r$  linear diagrams shown in Fig. 7, passing through the origin and the experimental points at  $g_r = 1$ . The calculated  $\bar{q}_c$  values are shown by the solid lines plotted in Fig. 8. These plots indicate close agreement between the theoretical and experimental values of  $\bar{q}_c$  at  $g_r$  levels of  $\frac{1}{6}$  and 1. Furthermore, the values of  $G$  and  $\bar{q}_c$  for both soils

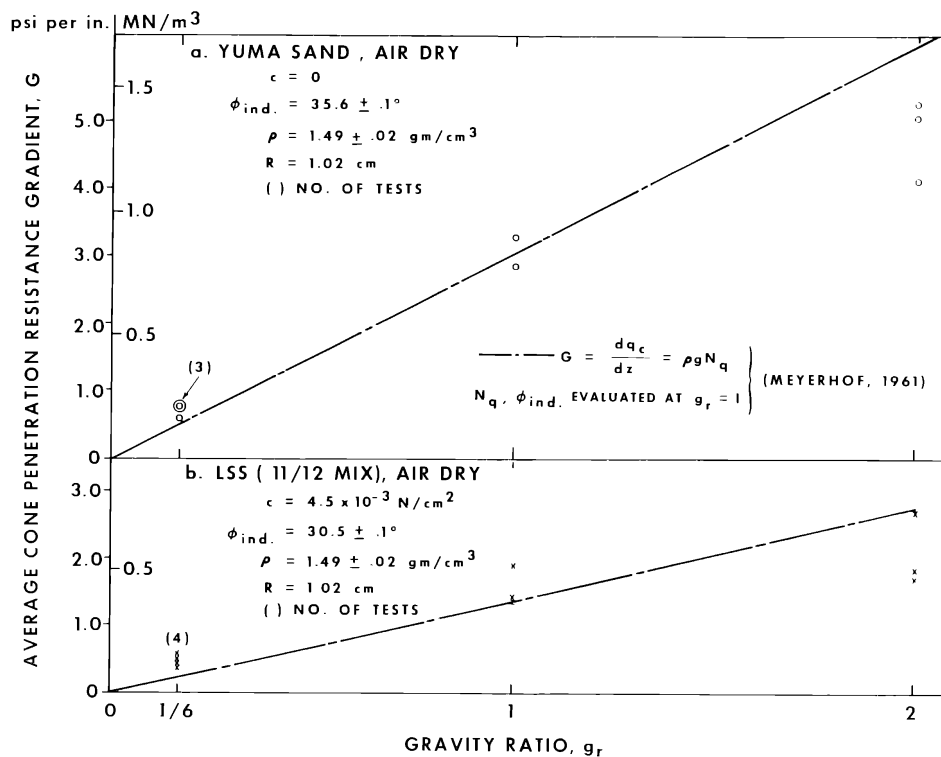


Fig. 7. Cone penetration resistance tests on Yuma Sand and LSS under varying gravity conditions. Average cone penetration resistance gradient,  $G$ , over 0–15 cm depth vs. gravity ratio,  $g_r$ .

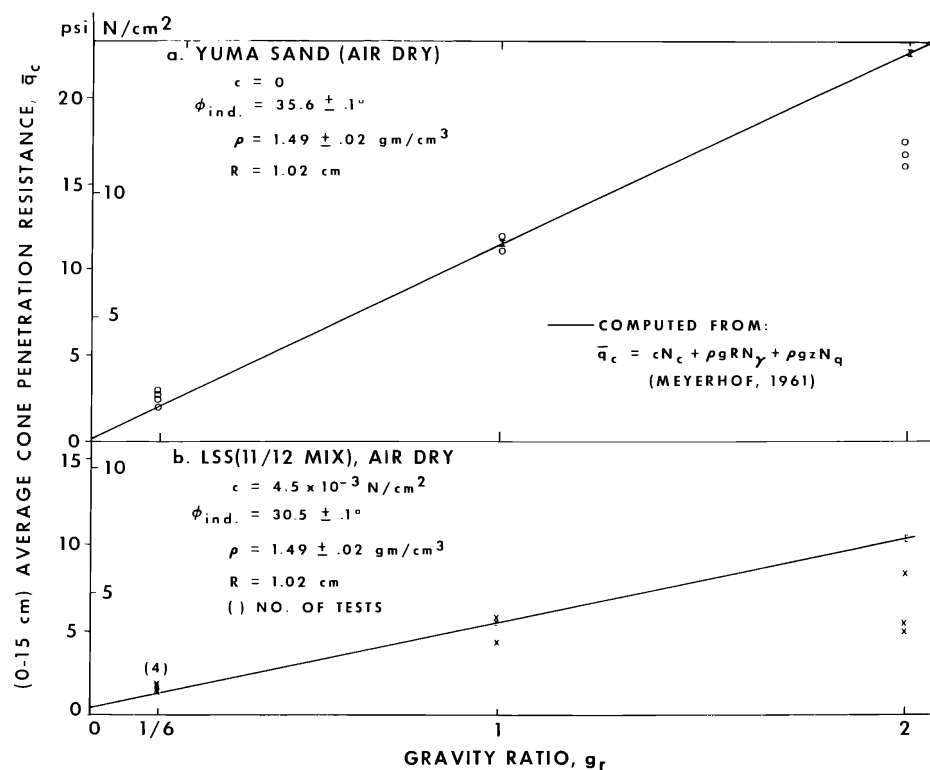


Fig. 8. Cone penetration resistance tests on Yuma Sand and LSS under varying gravity conditions. Comparison between  $\bar{q}_c$  experimental data and theoretical values calculated from bearing capacity theory (MEYERHOF, 1961), according to method I at  $g_r = 1$ .

at  $g_r = 1$  are in close agreement with results of cone penetration tests performed on both soils at comparable densities under terrestrial gravity conditions (Figs. 4 and 5). The apparent discrepancies from linearity in the  $G$  and  $\bar{q}_e$  values for both soils at gravity ratio levels of “2  $g$ ” are tentatively attributed to uncertainties regarding the exact  $g$  level achieved by the aircraft during the 2  $g$  maneuvers.

#### EVALUATION OF LUNAR SOIL PENETRATION DATA FROM APOLLO 11 AND APOLLO 12

The analysis of the cone penetration tests reported herein indicates that penetration resistance profiles in soils similar to those found on the lunar surface provide sensitive indicators of the variation of the in-place dry bulk density of the soil with depth and can be analyzed by bearing capacity theory to estimate the in-situ shear strength characteristics of the material. During the Apollo 11 and Apollo 12 missions, various shafts, staffs, and tubes were inserted in the lunar surface (COSTES *et al.*, 1970; COSTES and MITCHELL, 1970; and SCOTT *et al.*, 1970). Although the circumstances under which these penetrations were performed, the type of apparatus used and the uncertainties in estimating the forces exerted by the astronauts in pushing these shafts into the lunar surface do not permit a rigorous analysis of these penetrations, the data can be used in conjunction with the penetration resistance tests on the LSS reported herein to make a first-order evaluation of the in-place density and the shear strength characteristics of the lunar soil in the upper few centimeters of the two Apollo sites.

From these considerations, upper bounds of the lunar soil in-place bulk density and angle of internal friction were obtained (Table 1) by analyzing the Apollo 11 and Apollo 12 soil penetration data according to the methods developed in this paper and making the following assumptions: (1) the hollow shafts used as penetrators became plugged at a shallow depth and subsequently behaved as flat-ended penetrators; (2) the maximum downward force exerted by a suited astronaut in pushing these penetrators is of the order of 90  $N$  (COSTES and MITCHELL, 1970; WERNER, 1970); (3) the frictional and adhesive forces mobilized along the penetrator shafts were negligible as compared to the resistance of the soil to penetration at the “flat-ended” penetrator tips; and (4) the term  $cN_e$  is very small as compared to the sum of the other two terms on the right-hand side of equation (1) and may be neglected.

As shown in Table 1, assuming that at a given value of  $G$  the void ratio of the lunar soil (specific gravity of solids: 3.1) is the same as the corresponding void ratio of the LSS (specific gravity of solids: 2.89), upper bounds of the in-place lunar soil bulk density at the Apollo 11 and Apollo 12 sites should be of the order of 1.85  $g/cm^3$  and 1.81  $g/cm^3$ , respectively. Lunar-soil bulk density data (1.74  $g/cm^3$ , 1.96  $g/cm^3$ , and 1.98  $g/cm^3$ ) obtained from Apollo 12 core tube samples (SCOTT *et al.*, 1970) tend to corroborate these indicated density values. On the other hand, possible disturbances in the soil during sampling, caused by the design of the two Apollo 11 core tubes, may have resulted in underestimating the in-place bulk density of the lunar soil at the Apollo 11 site, as determined from the corresponding core tube sample bulk density measurements (1.59  $g/cm^3$  and 1.71  $g/cm^3$ ) (COSTES *et al.*, 1970; COSTES and MITCHELL, 1970; SCOTT *et al.*, 1970).

Table 1. Evaluation of in-place soil mechanical properties at Apollo 11 and Apollo 12 sites from in-situ soil penetration data

|                  | (1)       | (2)       | (3)                        | (4)                          | (5)                             | (6)                   | (7)                        | (8)                 | (9)                                            |
|------------------|-----------|-----------|----------------------------|------------------------------|---------------------------------|-----------------------|----------------------------|---------------------|------------------------------------------------|
|                  | $R$<br>cm | $z$<br>cm | $q_z$<br>N/cm <sup>2</sup> | $G_L^*$<br>N/cm <sup>3</sup> | $\rho_L^*$<br>g/cm <sup>3</sup> | $\phi_L^*$<br>degrees | $G_L$<br>N/cm <sup>3</sup> | $\phi_L$<br>degrees | $c_L$<br>$\times 10^{-2}$<br>N/cm <sup>2</sup> |
| Apollo 11        |           |           |                            |                              |                                 |                       |                            |                     |                                                |
| Contingency      |           |           |                            |                              |                                 |                       |                            |                     |                                                |
| Sampler Holder   | 0.80      | 20        | 45                         | 2.2                          | 1.92                            | 48                    |                            |                     | 44†                                            |
| Flagpole         | 1.11      | 18        | 23                         | 1.3                          | 1.86                            | 45                    |                            |                     | 21†                                            |
| Core Tube        | 1.66      | 7.5–13    | 10                         | 1.3–0.75                     | 1.86–1.82                       | 45–43                 | 0.18†                      | 36.8†               | 9.2–8.1†                                       |
| Solar Wind       |           |           |                            |                              |                                 |                       |                            |                     |                                                |
| Composition      |           |           |                            |                              |                                 |                       |                            |                     |                                                |
| Experiment Staff | 1.70      | 14        | 9.9                        | 0.66                         | 1.81                            | 42                    |                            |                     | 7.5†                                           |
| Apollo 12        |           |           |                            |                              |                                 |                       |                            |                     |                                                |
| Core Tube        | 1.66      | 10–18     | 10                         | 0.96–0.55                    | 1.84–1.80                       | 44–42                 | 0.24‡                      | 37.7‡               | 7.5–5.6‡                                       |
| Solar Wind       |           |           |                            |                              |                                 |                       |                            |                     |                                                |
| Composition      |           |           |                            |                              |                                 |                       |                            |                     |                                                |
| Experiment Staff | 1.70      | 15        | 9.9                        | 0.62                         | 1.80                            | 42                    |                            |                     | 5.9‡                                           |

(1) Penetrator radius.

(2) Penetration depth.

(3) Average resistance to penetration of lunar soil at penetrator tip to an applied force of the order of 90  $N$ .

(4) Average penetration resistance gradient of lunar soil under lunar gravity conditions, estimated from equation (1) under the assumption that the term  $cN_c$  can be neglected.

(5) Upper-bound estimate of in-place lunar soil bulk density, determined from the  $G_E$  vs.  $\rho$  plot for LSS, assuming that  $G_E^* = 6 G_L^*$  and that at a given  $G$  value the void ratio of the LSS is the same as that of the lunar soil.  $G_E$  = penetration resistance gradient of lunar soil under terrestrial gravity conditions.

(6) Upper-bound estimate of in-place angle of internal friction of lunar soil, based on  $G_L^*$  and  $\rho_L^*$  and determined according to method I.

(7) Average in-place penetration resistance gradient of lunar soil, estimated from equation (1) on the basis of measured value of  $\rho_L$ .

(8) In-place angle of internal friction of lunar soil, estimated from equation (1) on the basis of measured value of  $\rho_L$ .

(9) In-place cohesion of lunar soil, estimated from equation (1) on the basis of measured value of  $\rho_L$ .

† Estimated from equation (1) on the basis of a measured average bulk-density value of 1.71 g/cm<sup>3</sup>, obtained from Apollo 11 core-tube sample 10005 (COSTES and MITCHELL, 1970).

‡ Estimated from equation (1) on the basis of a measured average bulk-density value of 1.74 g/cm<sup>3</sup>, obtained from Apollo 12 core-tube sample (Core Tube Serial No. 2011) (SCOTT *et al.*, 1970).

On the basis of triaxial compression tests performed on LSS (COSTES *et al.*, 1969; MITCHELL *et al.*, 1970), the indicated upper-bound values for the in-place angle of internal friction of the lunar soil at the two Apollo sites shown in Table 1 are compatible with the corresponding upper-bound estimates of the in-place lunar soil bulk density.

Finally, by solving equation (1) for  $c$  on the basis of the measured bulk density values of 1.71 g/cm<sup>3</sup> and 1.74 g/cm<sup>3</sup>, the angle of internal friction of the lunar soil at the corresponding Apollo 11 and Apollo 12 core tube sites is estimated to be 36.8 deg and 37.7 deg, and its cohesion to be of the order of  $9 \times 10^{-2}$  N/cm<sup>2</sup> and  $7 \times 10^{-2}$  N/cm<sup>2</sup>, respectively. Based on the same density measurements and penetration data from the locations shown in Table 1, the lunar soil cohesion is estimated to vary between  $7.5 \times 10^{-2}$  N/cm<sup>2</sup> and  $4.4 \times 10^{-1}$  N/cm<sup>2</sup> at the Apollo 11 site and between  $5.6 \times 10^{-2}$  N/cm<sup>2</sup> and  $7.5 \times 10^{-2}$  N/cm<sup>2</sup> at the Apollo 12 sites. These

estimates are in agreement with independent observations and measurements associated with the analysis of lunar soil mechanics data obtained from the Surveyor and Apollo 11 missions (SCOTT and ROBERSON, 1968; COSTES *et al.*, 1970).

### CONCLUSIONS

(1) Studies on the mechanical behavior of simulated lunar soils have assisted in gaining a better understanding of the actual lunar soil observed during the Apollo 11 and Apollo 12 EVA's. (2) The cone penetration resistance of soils similar to the actual lunar soil is a sensitive indicator of the grain-size distribution and in-place packing characteristics and consistency of the soil. Therefore, it can furnish corroborative information relative to the in-situ physical properties and stratification of lunar soil that can prove to be very useful to other scientific disciplines. (3) Through bearing capacity theory, results of cone penetration resistance tests on lunar soil simulants can be used in conjunction with soil bulk density data to determine the in-place shear strength characteristics of such soils. (4) Estimates of the in-situ bulk density of the lunar soil in the upper few centimeters at the Apollo 11 and Apollo 12 sites, based on cone penetration resistance tests on lunar soil simulants and crude soil penetration resistance data from the two missions, are in agreement with lunar soil bulk density measurements from Apollo 12 core tube samples. Estimates of the in-place cohesion and angle of internal friction of the lunar soil at the same locations, based on the same data, are in agreement with previous estimates based on independent measurements and observations. (5) The mechanical properties of the lunar soil at the Apollo 11 and Apollo 12 sites, as evaluated from this analysis, appear to be of the same order of magnitude as those of the soils encountered at the Surveyor equatorial landing sites.

*Acknowledgements*—The assistance offered in this research program by: the Simulation Branch, Astronautics Laboratory, NASA/MSFC; Zero-g Test Office, Wright-Patterson Air Force Base; and the Astronaut Office and Flight Crew Support Division, NASA/MSC is greatly appreciated.

The senior author wishes to express his sincere appreciation to all of his former and current colleagues at the MSFC Space Sciences Laboratory for their excellent cooperation and enthusiasm in contributing to various facets of these investigations. Finally, many thanks go to Dr. K. J. MELZER of the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi for his generous permission to analyze cone penetration data collected by him and to be reported in a forthcoming publication.

### REFERENCES

- COSTES N. C. *et al.* (1969) Lunar soil simulation studies in support of Apollo 11 mission. NASA Technical Memo, Geotechnical Research Laboratory, Space Sciences Laboratory, Marshall Space Flight Center, Huntsville, Alabama.
- COSTES N. C., CARRIER W. D., MITCHELL J. K., and SCOTT R. F. (1970) Apollo 11: Soil mechanics results. *ASCE J. Soil Mech. Foundations Div.* **7704**, 2045–2080.
- COSTES N. C. and MITCHELL J. K. (1970) Apollo 11 soil mechanics investigation. *Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 1, Vol. 2, pp. 2025–2044. Pergamon.
- FREITAG D. R. (1965) A dimensional analysis of the performance of pneumatic tires on soft soils. Technical Report 3-688, U.S. Army Engineering Waterways Experiment Station, CE (USAE WES), Vicksburg, Mississippi.

- FREITAG D. R., GREEN A. J., and MELZER K. J. (1970) Performance evaluation of wheels for lunar vehicles. Technical Report M-70-2, USAE WES, Vicksburg, Mississippi.
- DEPARTMENT OF THE ARMY (1959) Soils trafficability. Technical Bulletin TB ENG 37, Headquarters, Department of the Army, Washington, D.C.
- DUKE M. B., WOO C. C., SELLERS G. A., BIRD M. L., and FINKELMAN R. B. (1970) Genesis of lunar soil at Tranquillity Base. *Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta* Suppl. 1, Vol. 1, pp. 347–361. Pergamon.
- GREEN A. J. and MELZER K. J. (1970) Performance of Boeing-GM wheels in a lunar soil simulant (basalt). Technical Report M-70-15, USAE WES, Vicksburg, Mississippi.
- HVORSLEV M. J. (1970) The basic sinkage equations and bearing capacity theories. Technical Report M-70-1, USAE WES, Vicksburg, Mississippi.
- MELZER K. J. (1968) Sondenuntersuchungen im Sand (Penetrometer investigations in sand), Dissertation, Technical University of Aachen. Published in *Mitteilungen Institut für Verkehrswasserbau, Grundbau und Bodenmechanik* 43, Technical University of Aachen, Germany.
- MELZER K. J. (1971) Measuring soil properties in vehicle mobility research. Report 4, Relative density and cone penetration resistance. Technical Report 3-652, U.S. Army Materiel Command.
- MEYERHOF G. G. (1961) The ultimate bearing capacity on wedge-shaped foundations. *Proc. Fifth Int. Conf. Soil Mech. Foundation Eng.*, Vol. 2, pp. 105–109, Dunod, Paris.
- MITCHELL J. K., CARMICHAEL I. S. E., GOODMAN R. E., FRISCH J., WITHERSPOON P. A., and HEUZE F. E. (1969) Materials studies related to lunar surface explorations. Final Report on NASA Contract NSR 05-003-189 submitted to George C. Marshall Space Flight Center by Space Sciences Laboratory, University of California, Berkeley.
- MITCHELL J. K., HOUSTON W. N., GOODMAN R. E., WITHERSPOON P. A., VINSON T. S., DURGUNOGLU T., NAMIQ L. I., THOMPSON J. B., and THREADWELL D. (1970a, b) Lunar surface properties experiment definition. Final Report on NASA Contract NAS 8-21432 submitted to George C. Marshall Space Flight Center by Space Sciences Laboratory, University of California, Berkeley.
- POWELL C. J. and GREEN A. J. (1965) Performance of soils under tire loads; analysis of tests in Yuma Sand through August 1965. Technical Report 3-666, Report 2, USAE WES, Vicksburg, Mississippi.
- SANGLERAT G. (1967) El penetrometro y el reconocimiento des los suelos (Penetrometers and subsoil exploration). Servicio de Publications, Ministerio de Orbas Publicas, Madrid.
- SCHULTZE E. and MUHS H. (1967) *Bodenuntersuchungen für Ingenieurbauten (Soil Investigation for Engineering Structures)*. Second ed., Springer-Verlag, Berlin.
- SCOTT R. F. and ROBERSON R. I. (1968) Soil mechanics surface sampler. Chapt. V, pp. 135–185. Surveyor Project Final Report, Part II: Science Results, Jet Propulsion Laboratory, California Institute of Technology, TR32–1265.
- SCOTT R. F., CARRIER W. D., COSTES N. C., and MITCHELL J. K. (1970) Mechanical properties of the lunar regolith. Apollo 12 Preliminary Science Report, NASA SP-235, pp. 161–188.
- SMITH R. E. (1969) Evaluation of the physical properties of lunar soils. ASEE/NASA Faculty Fellowship Program.
- TERZAGHI K. and PECK R. B. (1948) *Soil Mechanics in Engineering Practice*. John Wiley.
- TURNAGE G. W. (1971) Performance of soils under track loads; model track and test program. Technical Report (in preparation), USAE WES, Vicksburg, Mississippi.
- VESIC A. S. (1967) Bearing capacity and settlement of foundations. Proc. of a Symposium held at Duke University, April 5–6, 1965, Durham, North Carolina.
- WERNER R. A. (1970) Human vertical force exertion capability at  $\frac{1}{6}g$ . Lockheed Electronics Company Technical Working Paper LEC/HASD No. 645 D. 21.052, NASA Contract NAS 9-5191, NASA Manned Spacecraft Center, Houston, Texas.
- WES (1945) Trafficability of soils. Technical Report (unnumbered), USAE WES, Vicksburg, Mississippi.