BEARING STRENGTH OF LUNAR SOIL

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Abstract. Bearing load vs penetration curves have been measured on a 1.3 g sample of lunar soil from the scoop of the Surveyor 3 soil mechanics surface sampler, using a circular indentor 2 mm in diameter. Measurements were made in an Earth laboratory, in air. This sample provided a unique opportunity to evaluate earlier, remotely controlled, in-situ measurements of lunar surface bearing properties. Bearing capacity, measured at a penetration equal to the indentor diameter, varied from 0.02–0.04 N cm^{-2} at bulk densities of 1.15 g cm^{-3} to 30–100 N cm^{-2} at 1.9 g cm^{-3}. Deformation was by compression directly below the indentor at bulk densities below 1.61 g cm^{-3}, by outward displacement at bulk densities over 1.62 g cm^{-3}. Preliminary comparison of in-situ remote measurements with those on returned material indicates good agreement if the lunar regolith at Surveyor 3 has a bulk density of 1.6 g cm^{-3} at 2.5 cm. depth; definitive comparison awaits both better data on bulk density of the undisturbed lunar soil and additional mechanical-property measurements on returned material.

1. Introduction

Prior to the return of lunar soil samples to Earth, a number of measurements of the mechanical properties of lunar soil were made from spacecraft. (Refs.: Kuiper, 1965; Moore, 1965; Jaffe, 1965, 1967a and b, 1968; Jaffe and Scott, 1966; Christensen *et al.*, 1967a and b, 1968a and b; Scott and Roberson, 1968, 1969; Choate *et al.*, 1969; Cherkasov *et al.*, 1967, 1968a and b; Cherkasov and Shvarev, 1968; Filice, 1967; Eggleston, 1968; Halajian, 1967; Karafiath and Nowatzki, 1968.) No equipment specifically designed for such measurements was carried on spacecraft, except the soil penetrometer on Luna 13 (Cherkasov *et al.*, 1968a). The Surveyor Soil Mechanics experiment utilized a device designed primarily as a soil sampler (Scott, 1967). In general, the soil mechanical properties were determined utilizing imaging and other equipment that was aboard the spacecraft for other purposes.

The problem of measuring surface mechanical properties, without returned samples, will probably arise for other planets. As a guide in evaluating probable techniques, it seems worthwhile to compare measurements of soil mechanical properties made on the moon, as mentioned above, with mechanical property measurements on lunar soil returned to Earth.

A unique opportunity for comparative measurements was provided by the return to Earth of 6.5 g of lunar soil contained in the scoop of the Surveyor 3 Soil Mechanics Surface Sampler, together with the scoop itself. This scoop had been used to measure soil properties on the Moon during Surveyor 3 operations (Scott and Roberson, 1968). Other soil property measurements had been made within a meter or so of the same spot using other equipment on Surveyor 3 (Christensen *et al.*, 1968a). The scoop and the soil within it were removed and returned to Earth by Apollo 12 astronauts Conrad and

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Bean. This soil sample, then, had been used in mechanical property measurements on the Moon and could be again used for such measurements on Earth.

This paper reports on one aspect of the on-earth laboratory measurements: bearing strength and bearing load-penetration relations, measured in air as a function of bulk density.

2. Material

After the scoop of the Surveyor 3 surface sampler was returned to the Lunar Receiving Laboratory in Houston, it was placed in a polyethylene bag. During subsequent handling, some of the lunar soil in the scoop fell out into the bag. This soil was recovered, and 1.3 g of it was provided by NASA for this and related investigations.

The few particles larger than about 1 mm had been removed by hand, but the soil had not been sieved or otherwise intentionally fractionated. Particle size distribution, measured on part of the 1.3 g sample, will be reported elsewhere.

The material was stored in air during and after its transfer to Earth.

The sample used is Apollo 12029-3-1.

3. Equipment

A commercial vertical, screw-driven, tension/compression testing machine equipped for recording load vs deformation, was used. Full-scale load-recording ranges extended from 2 g upward. As the lower ranges could only be used in tension, the test fixture was designed accordingly. The cup which contained the soil under test had an inside diameter of 1.0 cm and depth of 1.1 cm and was made of poly(methyl methacrylate). (For the first tests, the I.D. was 0.6 cm.) The bearing load was applied by a vertical rod, 2.0 mm in diameter. The rod tip tapered inward about 0.35 mm on the diameter in the 5 to 9 mm above the end to provide friction relief on the sides of the rod as it penetrated the soil. The rod was integral with a cylindrical brass weight suspended by a thin wire from the load cell at the top of the test machine.

4. Procedure

For the low bulk densities, soil was gently brushed into the cup from its top, or spooned in with a spatula. For high packing densities, the cup was tapped or, in a few cases, vibrated. Density was determined by weighing on an analytical balance and measuring the depth optically or on radiographic prints. Radiography was used in many runs to check freedom from voids larger than the particle size. Bulk densities obtained ranged from 1.15 to 1.93 g cm^{-3}.

Tests were made in air at 70°C; relative humidities were recorded as 40–50%. To test, the cup containing the soil was driven upward against the rod tip at the rate of 0.0021 cm s^{-1} (0.05 in./min). Motion was measured as travel of the lower cross-head, load as reduction of the weight suspended from the upper cross-head. Runs were generally started with the recording system at high sensitivity. If the load went off scale, cross-head motion was stopped, the load recorder was switched to lower sensitivity and cross-head motion resumed.

After test, the surface of the material was observed and changes were noted. Some specimens were again radiographed after test to provide further information on the nature of the deformation.

5. Results

No voids were visible in radiographs made prior to test. Some small denser clumps were noted before test in one run with a bulk density of 1.26 g cm^{-3}; the other specimens radiographed appeared to be uniform before test.

Figure 1 shows bearing stress vs penetration curves for four of the runs. At low

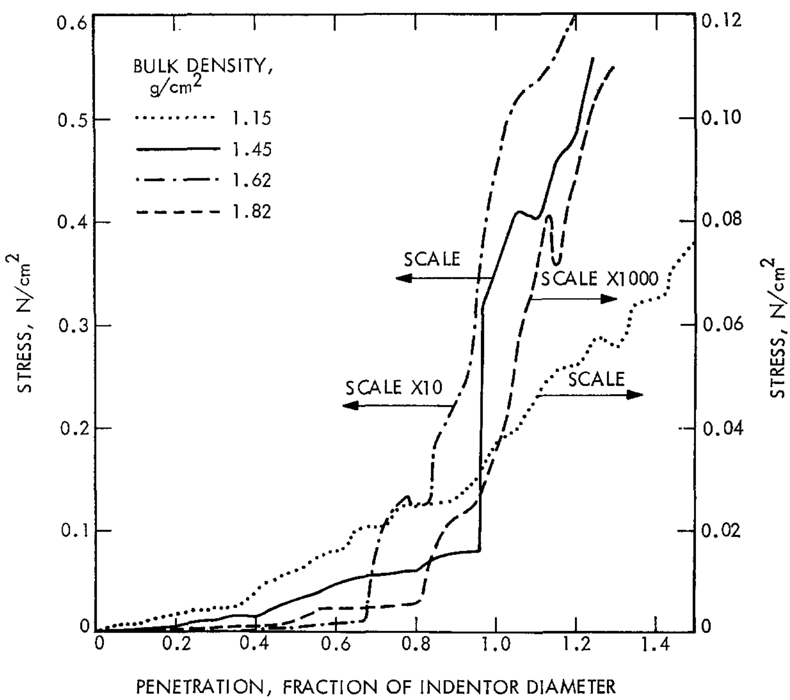

Fig. 1. Bearing stress vs penetration. Four individual test runs, at various bulk densities, are plotted. Note different vertical scales. Indentor tip diameter = 2 mm.

penetrations, the relation was roughly linear, with some tendency to curve toward higher force as the penetration increased. In most of the runs at medium and high bulk densities, the slope of the stress-penetration curves then suddenly increased sharply, leading to a rapid increase in stress, often amounting to an order of magnitude or more (see Figure 1). A few of the runs at high bulk density showed one or more decreases in load with increasing penetration; these load decreases were generally accompanied by visible local bulging of the top surface of the material.

The top surfaces after test showed bulging and cracking for all runs at bulk densities above 1.62 g cm^{-3}. No cracking or bulging was observed for any run below 1.61 g cm^{-3} (except for a small amount of bulging in one run at 1.42 g cm^{-3}). Radiographs after test were in complete agreement with these visual observations. For material of low bulk density ,it was usually possible to see in these radiographs a cylindrical plug of denser material directly below the indentor hole. The holes retained their vertical sides after the indentor was withdrawn, displaying the soil cohesion.

6. Discussion

The shape of the stress-penetration curves agreed with those ordinarily found for terrestrial particulate materials with corresponding bulk densities and relatively low cohesion, except for the initial low stress level, followed by the sudden slope increase. To elucidate these characteristics, bearing tests were made on crushed terrestrial basalt, with a particle size distribution and mechanical properties resembling the lunar material. In these tests larger indentors (6 mm diameter) and larger cups (150 mm diameter, 75 mm depth) were used, as well as the small ones used for the lunar material. Lunar material could not be tested with the larger cups and indentors as the sample was too small. Sudden slope increases were found with the terrestrial basalt tested with the 2 mm diameter indentor. With the larger indentor, in the large cup, the initial low stress level and sudden slope increase were never found; instead, the stress level immediately rose to levels corresponding to those encountered after a sudden increase. Tests using the 2 mm indentor in the large cup showed that the initial low stress, followed by the sudden increase, was characteristic of packing procedures in which a thin loose layer of material was placed on a well-compacted substrate, and the cup then tapped to compact the material further. It appears, therefore, that the low initial stress level was due to a surface layer of lower density than that below. Placement of particulate material in the small cup, followed by tapping, is apparently likely to lead to this condition.

Accordingly, the stress levels before the sudden slope increase are probably not representative of the overall bulk density. In most runs where such an increase occurred with lunar material, the increase took place before penetration reached 1 indentor diameter. The stress at penetration equal to 1 indentor diameter was taken as the bearing capacity (Table I). In a few cases, in which a sudden increase occurred at high penetration, or the indentor tilted before penetration equalled 1 diameter, the curve was extrapolated to this penetration.

In general, when motion of the testing machine head was stopped to permit switching the range of the load sensor, the load promptly fell to zero or almost zero. When indentor motion was resumed, the load rose rapidly to its previous value, but a detectable penetration occurred during the load increase. This penetration was deducted in the analysis of stress-vs-penetration curves.

The bearing capacity is plotted vs bulk density in Figure 2. Despite the scatter, the trend is obvious. Drawn in the figure is a linear least squares fit for log of the bearing

TABLE I

Bearing capacity and density of lunar soil

Bulk density g/cm^{-3}	Bearing capacity at penetration = 1 indentor diameter N/cm^{-2}	Remarks	Cracking and bulging
1.15	0.038		No
1.18	0.027		No
1.22	0.038	6 mm cup diameter	–
1.26	0.021		No
1.42	0.048		No (minor bulging)
1.45	0.35		No
1.46	1.9		No
1.48	0.82		No
1.54	1.4		No
1.60	5.6	Extrapolation of stress-penetration curve. 6 mm cup	–
1.61	8.2		Yes
1.62	4.4		No
1.70	6.2		Yes
1.70	10		Yes
1.76	12.5	Extrapolation	Yes
1.79	> 6.2	Extrapolation	Yes
1.80	16		Yes
1.82	11	Extrapolation	Yes
1.83	100	At yield	Yes
1.84	33		Yes
1.84	36		Yes
1.86	> 6.2	Extrapolation	Yes
1.90	32		Yes
1.93	> 6.2	Extrapolation	Yes

capacity, p, vs bulk density, d, corresponding to the relation

$$\log_{10} p = -6.94 + 4.62\, d, \qquad (1)$$

where p is in $N\,cm^{-2}$ and d in $g\,cm^{-3}$. The standard deviation is equivalent to a difference of $0.06\,g\,cm^{-3}$ in bulk density. A slightly better fit was obtained with a quadratic least-squares, but the improvement was not statistically significant.

7. Comparison with Lunar Results

To compare the laboratory results with on-Moon measurements, it is necessary to know the bulk density in-situ on the Moon. Unfortunately, no reliable measurements of lunar regolith density have been published. The in-situ measurements by Luna 12 (Morozov *et al.*, 1968; Cherkasov *et al.*, 1967) are ambiguous and questionable (Scott, 1968); measurements on cores returned by Apollo 11 and 12 undoubtedly reflect significant disturbances on packing caused by insertion of the core tubes themselves (Lunar Preliminary Examination Team, 1969; Scott *et al.*, 1970). Indeed, the author attempted to calculate density from the in-situ bearing strength measurements, ob-

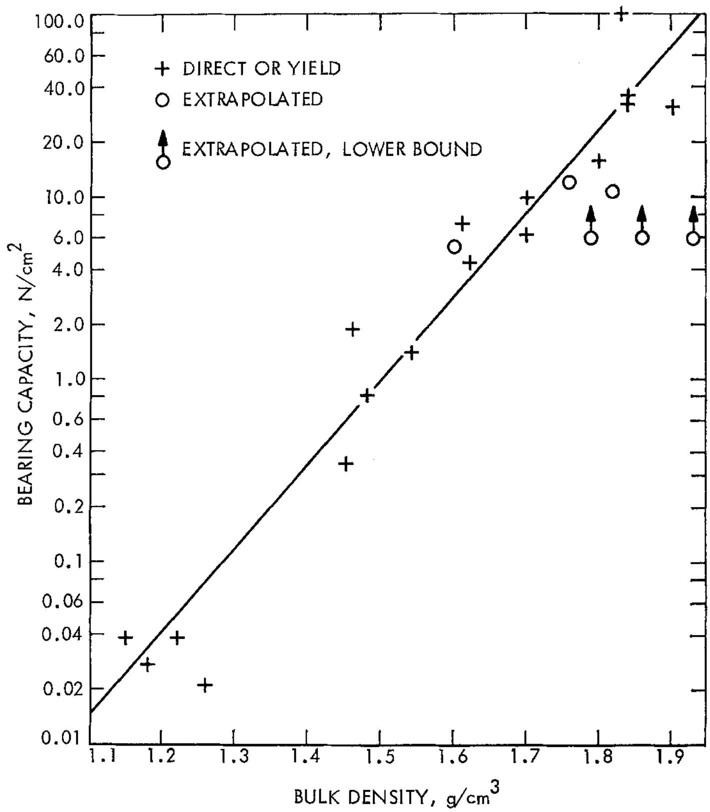

Fig. 2. Bearing capacity vs bulk density. Line indicates least-squares fit. Bearing capacity taken at a penetration equal to indentor diameter.

taining 1.1 g cm^{-3} at the surface and 1.6 g cm^{-3} at 5 cm depth (Jaffe, 1969). Perhaps the best results at the moment are those from Apollo 12 core tubes, indicating that the bulk density probably averages about 1.8 g cm^{-3} for the top 30 cm of material (Scott *et al.*, 1970). The corresponding bearing capacity shown by Figure 2 is about 20 N cm^{-2}.

The in-situ bearing data providing the most direct comparison with the present measurements are those of Scott and Roberson (1968), using the same Surveyor 3 soil mechanics surface sampler, with its scoop closed, at positions including that from which the soil sample used in the present work was obtained, and all within 1.5 m of it. Scott and Roberson obtained a bearing pressure of 2 N cm^{-2} at a depth of 2.5 cm and bearing plate width of 2.5 cm. Other nearby Surveyor 3 soil bearing stress measurements included 10 N cm^{-2}, for depths of 4–5 cm and bearing plate width of 0.32 cm, from the surface sampler with scoop open (Scott and Roberson, 1968), and 4 N cm^{-2} for depth of about 2.5 cm and bearing diameter about 25 cm, from a footpad indentation (Christensen *et al.*, 1968a).

The closed-scoop surface sampler value of 2 N cm^{-2} was obtained at a (penetration depth)/(bearing plate width) ratio of 1, corresponding to the condition used for Figure 2. Match to the curve of Figure 2 occurs not a bulk density of 1.8 g cm^{-3}, but at about 1.6 g cm^{-3}. This tends to suggest that the bulk density of the lunar soil at Surveyor 3, and a depth of 2.5 cm, is about 1.6 and not 1.8 g cm^{-3}. Corrections to the bearing strengths should, in principle, be made for differences in scale, geometry, gravity, and perhaps atmosphere. It seems best, however, to await results of other tests, including shear tests, planned for the same sample of lunar soil, before attempting those corrections.

A roughly linear stress-vs-penetration curve for linear soil was found in in-situ measurements at the Surveyor 7 site, near Tycho, using a soil mechanics surface sampler (Scott and Roberson, 1969). The bearing capacity observed with the scoop was essentially the same as at Surveyor 3, described above (ibid).

Other Surveyor and Lunar Orbiter results have been summarized by the author (Jaffe, 1969). The indicated bearing capacity was about 0.1 N cm^{-2} at 0.1 cm depth and 1.7 N cm^{-2} at 2 cm depth. Whether this variation is due to change of bulk density with depth remains to be determined.

Observations on the lunar surface by Apollo 11 astronauts gave stresses of 0.5–1.5 N cm^{-2} for penetration/diameter or penetration/width ratios $\leqslant 1$, and depths of 1 to 8 cm (Costes *et al.*, 1970). The present laboratory results seem consistent with these observations.

Tests by Costes *et al.* (1970) on lunar soil returned by Apollo 11, in which a penetrometer was inserted to the depth necessary to reach a fixed load, gave, at a penetration/diameter ratio near 1, bearing stress of about 1 N cm^{-2} at a bulk density of 1.14 g cm^{-3}, <5 to 14 N cm^{-2} at 1.77 g cm^{-3}, and 30 N cm^{-2} at 1.80 g cm^{-3}. The results at 1.77–1.80 g cm^{-3} are consistent with those found in this work; that at 1.36 g cm^{-3} is higher by X5 than the value indicated by Figure 2. The failure modes in the laboratory tests of Apollo 11 material were the same as in the present tests.

8. Conclusions

(1) Bearing capacities of lunar soil returned from Surveyor 3 vary from 0.02-0.04 N cm^{-2} at a bulk density of 1.15 g cm^{-3} to 30–100 N cm^{-2} at 1.9 g cm^{-3}. The relation between bulk density and logarithm of the bearing capacity is roughly linear. These results are for measurements with an indentor of 2 mm diameter, in air, on Earth, and at penetration equal to the diameter of the indentor.

(2) The shapes of the load-penetration curves are similar to those obtained with particulate material of terrestrial origin.

(3) At bulk densities below 1.61 g cm^{-3}, deformation was by compression of the material below the indentor ('local shear', 'compressible failure'). At bulk densities above 1.62 g cm^{-3}, deformation was by outward displacement of the material (general shear', 'incompressible failure').

(4) Preliminary comparison with bearing measurements made in-situ on the Moon by remote-control techniques, prior to return of samples from the Moon, suggests good

agreement if the lunar material has a bulk density of about 1.6 g cm^{-3} at a depth of 2.5 cm. Definitive comparison waits on the availability of better data on bulk densities of the lunar soil and other tests of mechanical properties of returned materials, as well as further analysis.

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