Scott, R. F., Carrier, W. D., Costes, N. C. & Mitchell, J. K. (1971). *Géotechnique* **21**, No. 1, 1–14.

APOLLO 12 SOIL MECHANICS INVESTIGATION

R. F. Scott,* W. D. Carrier, III,† N. C. Costes‡ and J. K. Mitchell§

SYNOPSIS

During the sojourn of the second manned spacecraft on the moon in November 1969, the astronauts C. Conrad and A. Bean performed a number of tasks of interest from a soil mechanics point of view. They crossed the lunar surface, penetrating it with a variety of objects including core tube sampling devices, and visited an unmanned Surveyor spacecraft which had landed on and communicated from the moon 31 months previously. The mechanical behaviour of the lunar soil during these activities has been analysed and is found to be consistent with the properties of a slightly cohesive medium dense granular soil (under lunar gravity) as deduced from previous Surveyor experiments. The grain size distribution and mechanical behaviour of the lunar soil samples which were brought back to Earth are also examined.

Pendant le séjour sur la lune du second engin spatial habité en Novembre 1969, les astronautes C. Conrad et A. Bean exécutérent un certain nombre de travaux relevants de la mécanique des sols. Parmi ceux-ci ils percèrent la surface de la lune et y enfoncèrent un ensemble d'instruments, en particulier des tubes de carottier. Ils entreprirent aussi une inspection de Surveyor, engin lunaire non habité qui avait aluni et communiqué avec la terre 31 mois auparavant. Le comportement méchanique du sol lunaire durant ces activités est analysé ici. Ses propriétés peuvent être assimilées à celles d'un sol formé par un milieu granulaire moyennement dense et faiblement cohérent (soumis à la gravité lunaire); elles sont comparables à celles déduites des précédentes expériences Surveyor. La granulométrie et les propriétés méchaniques des échantillons de sol lunaire rapportés sont aussi examinés.

INTRODUCTION

The second manned lunar landing mission, Apollo 12, was launched on 14 November, 1969; the crew consisted of C. Conrad, Jr., A. L. Bean and R. Gordon. On 19 November the lunar module, containing astronauts Conrad and Bean, was detached from the command module in lunar orbit and landed on the surface of the moon in the eastern part of Oceanus Procellarum. The landing site was at 23·4° W and 3·2° S, approximately 120 km south-east of the crater Lansberg and due north of the centre of Mare Cognitum. This position is on a broad ray associated with the crater Copernicus, which is approximately 370 km to the north. The location had been selected as a target point beforehand because, on 20 April, 1967, the unmanned United States spacecraft Surveyor III had landed there in a 650 ft dia. crater. Surveyor had operated on the moon for two weeks during which it transmitted many pictures, and carried out among other experiments a number of tests of the mechanical nature of the lunar surface. Professor Scott was the experimenter in charge of these tests (Scott and Roberson, 1968) which were performed with a device referred to as the surface sampler.

It was considered that an examination of the earlier spacecraft by the astronauts and the return of some of its components to Earth could provide a great deal of scientific and engineering information of value to future spacecraft design and operations. To enable the astronauts to visit Surveyor the lunar module had to touch down within, at most, a few hundred yards of it and within sight of it. This was accomplished and the vehicle landed on the north-west rim of the Surveyor crater about 150 yards from the unmanned spacecraft. The general topography of the Apollo 12 landing site is characterized by a gently rolling surface that includes several large subdued craters and many smaller craters with raised rims. In the planning for

---

* Division of Engineering and Applied Science, California Institute of Technology.

† Manned Space Center, N.A.S.A., Houston.

‡ Marshall Space Flight Center, N.A.S.A., Huntsville.

§ University of California.

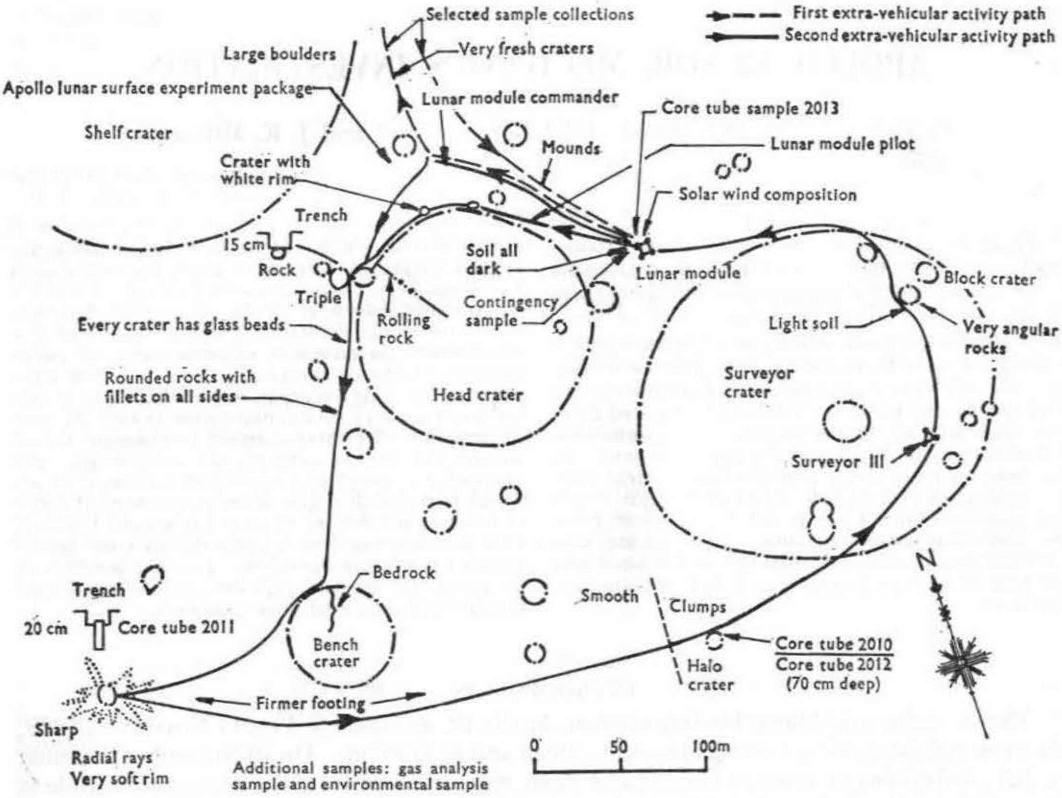


Fig. 1. Map of Surveyor III and lunar module landing site

the mission informal names were given to these craters, and these names are also used in this Paper (Fig. 1). The traverses made by the two astronauts were made around or in these features, as well as on the surface material consisting of ejecta deposits.

In the position in which it landed the lunar module sat on a relatively level surface, and was tilted at an angle of about 4° to the south-west. The vehicle has four shock-absorbing legs with circular 3 ft dia. footpads mounted at the ends. The four legs were rotated about 15° clockwise from the cardinal points of the compass, as the spacecraft sat, so that the $+z$ axis leg (the one to which the ladder was attached) pointed 15° north of west. The $+y$ axis, $-z$ axis and $-y$ axis legs pointed in directions about 15° clockwise from north, east and south respectively.

This Paper presents the results of a preliminary examination of the data, photographs and soil samples of the Apollo 12 mission, from a soil mechanics point of view. The various features of the descent, landing, and extra-vehicular activities of the astronauts are compared with those observed at the Apollo 11 landing site. Comments regarding the appearance of, and conditions around, the Surveyor III spacecraft which was visited by the Apollo 12 astronauts are also given. The report by Costes *et al.* (1969) on soil properties at the Apollo 11 landing site gives a summary of previous observations of the lunar surface and may be referred to for detailed comparison with the results of this study. The events of the Apollo 12 landing are described in chronological sequence.

DESCENT AND TOUCH-DOWN

Descent

The descent profiles of Apollo 11 and 12 lunar modules differed considerably in the last 200 ft. Apollo 11 descended at about 2 ft/s to a height (as measured from the surface to a level plane through the footpads) of about 5–8 ft, and then paused at this elevation for 13 s before descending the final 7 ft to the surface in 3 s. By comparison the lunar module of Apollo 12 made the last portion of the descent at about 1·5 ft/s with no pauses. On Apollo 11 the descent propulsion engine was not turned off until about 1 second after footpad contact, whereas on Apollo 12 the engine was shut down, according to Astronaut Conrad, as soon as the contact probes touched the lunar surface. This was at a footpad height above the surface of about 5 ft. The last few feet of descent of Apollo 12 therefore took place as a hindered free fall as the thrust of the descent engine decayed after shut-down.

Although final information on the spatial profile of the Apollo 12 descent is not available yet, the data to hand indicate a considerable difference between it and that of the Apollo 11 descent. The lateral velocity of the Apollo 11 vehicle was relatively high, at about 3 ft/s, for most of the final 20 or 30 s of flight. The Apollo 12 spacecraft approached at a lateral rate of about 1·5 ft/s and slowed down to just over 1 ft/s as it approached the landing site. The latter spacecraft thus covered a much shorter lateral distance on the surface during the final seconds of descent than did the Apollo 11 lunar module. It can be inferred that the same area of lunar surface suffered a more prolonged exposure to the blast of the descent engine of Apollo 12 than the corresponding area of the Apollo 11 landing.

Surface erosion and visibility problems

An examination of the frames of the cine film of the descent made during the Apollo 12 approach shows considerable movement of the lunar surface material to be taking place. This reached such a level that in the final stages of the descent no surface features were visible. The astronauts described a loss of visibility at this time. This occurrence poses a potential hazard to future lunar landings, and it is highly desirable to evaluate its causes. The two spacecraft of missions 11 and 12 followed different descent profiles to land in different regions of the moon and, in addition, the thrust of the Apollo 12 lunar module was higher by about 5% than that of Apollo 11. The impairment of visibility may be influenced by the lower angle of the sun at which the Apollo 12 landing was made. Also the amounts of erosion may be different because the descents, the surface soil, the thrusts, or a combination of these factors were different.

To determine the difference between the observed behaviours of the lunar surface during the two flights, a detailed examination of individual frames of the cine films of the descents was made. In this study the heights of the spacecraft at earlier stages in the descents were determined first by internal evidence in each frame (camera geometry, spacecraft dimensions and known crater dimensions) and then compared with heights deduced from the framing rates of

Table 1. Comparison of altitudes at which similar events occur on descent

Event	Altitude, ft (time to touch down, s)	
	Apollo 11	Apollo 12
First signs of blowing dust	80 (65)	110 (52)
Streaking fully developed	15 (21)	30 (21)
Loss of visibility	9 (15)	24 (17)

the cameras and the known descent profiles. Since good agreement was found between the heights determined by the two methods at the higher altitudes, the framing rate/descent profile technique was used with some confidence in the later stages of descent when the surface was partly or totally obscured. The results of the evaluation are presented in Table 1.

Loss of visibility was never as complete on the descent of Apollo 11 as on that of Apollo 12. It can be seen from Table 1 that the altitudes at which various events occurred on the descent of Apollo 12 are considerably greater than those in which similar events occurred in the Apollo 11 mission, as deduced from the cine film.

To explain this, a detailed analysis of all features related to erosion of the lunar surface by the descent engine is required. This has not been done yet, and only a few preliminary considerations have been examined. It can be seen from this Paper that the gross mechanical properties of the lunar surface material are not very different at the two landing sites, in terms of the depths of astronaut bootprints, penetration of the spacecraft into the surface and operation of various tools. However, the resistance of the surface to penetration by such objects depends on a number of factors such as cohesion, bulk density and grain size of the soil, and the angle of friction of the granular material. Erosion of the surface by the engine exhaust depends on the same factors, but to relatively different degrees. Thus erosion is more sensitive to grain size and cohesion and less so to friction angle and bulk density. Of two soils which both exhibit the same response (penetration depth) to an astronaut's boot because, say, one has a lower cohesion and higher friction angle than the other, the soil with the lower cohesion will be much more sensitive to erosion by a rocket engine. The evidence available of lunar surface material property variation is thus not sufficient at present to enable a decisive conclusion to be reached as to its effect on rocket erosion.

Laboratory examination of the soil returned from the lunar surface by the two missions indicates that the soil in the Apollo 12 core tubes possesses a substantially larger proportion of particles in the fine size range. However, the sieving technique was changed for the Apollo 12 analysis and should result in a greater breakdown of soil clumps and aggregates. It is therefore not clear yet if there is any fundamental difference between the materials. The distribution and proportion of particles larger than 0·1 mm in diameter from the different core tubes were similar. The Apollo 12 soil appears to get coarser with depth, but it is not known if this is significant in the erosion problem.

At present, therefore, the primary difference between the two landing sequences is that of the descent profiles and their effects on the rocket gas/surface interaction. This problem will be examined in detail to determine the extent of the contributions of the two processes which at present are analysed separately: particle entrainment by the gas flowing over the surface of the soil and pressure changes caused in the soil by the flow of gas into and through the voids. The first of these processes is analysed essentially as a time-independent phenomenon, whereas the second is a transient effect. If only the first is operating at the surface, the rate of erosion depends almost entirely on the engine nozzle height above the surface. If both are at work, which is more probable, the erosion rate depends on the nozzle height and the time during which the spacecraft stays at this altitude. With gas flow through the soil, the erosion rate increases with time for a given nozzle height (Scott and Ko, 1968).

Landing

Following engine shut-down when the footpads were about 5 ft above the lunar surface, the spacecraft fell as the engine thrust decayed, until the footpads made contact. The impact was relatively gentle, with stroking of the main shock absorbers limited to an inch or two at most. All the footpads except the $-y$ pad penetrated the surface only a small distance, of the order of one inch. The $-y$ footpad penetrated deeper, about 4 in., and disturbed the surface material to a greater extent than the others. The appearance of the surface around the $-y$

Fig. 2. Penetration of $-y$ footpad: footpad diameter 37 in.

Fig. 3. Crater $+y$ footpad and area under lunar module descent engine

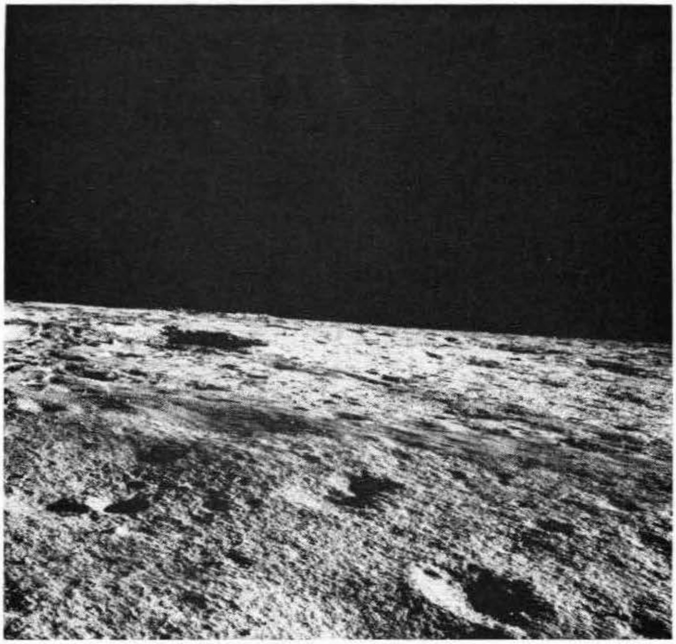


Fig. 4. Lunar surface 40–50 ft to east of lunar module showing surface erosion track

Fig. 5. Trench about 8 in. deep in the soft material on the east rim of Sharp crater

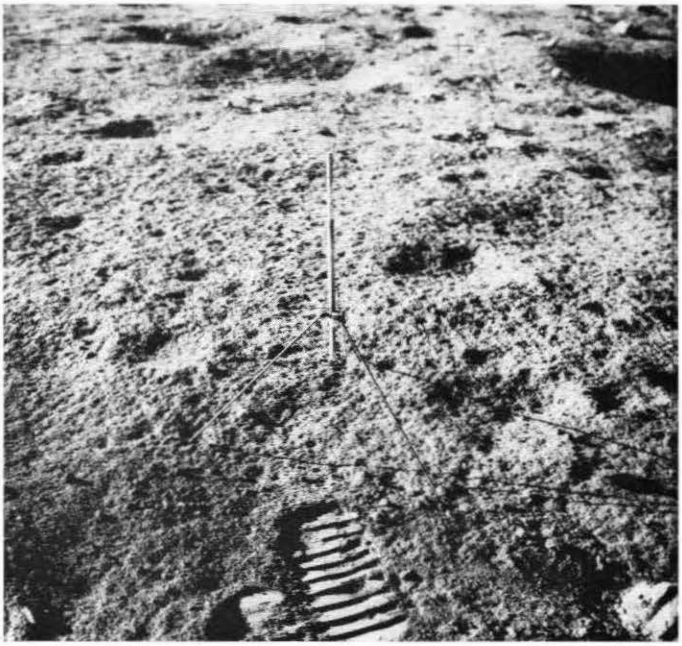


Fig. 6. Lunar surface in the vicinity of Halo crater showing lightly rained-on texture of undisturbed material and material compacted by astronaut's footstep. Gnomon gives lunar vertical

Fig. 7. Close-up of astronaut's bootprint

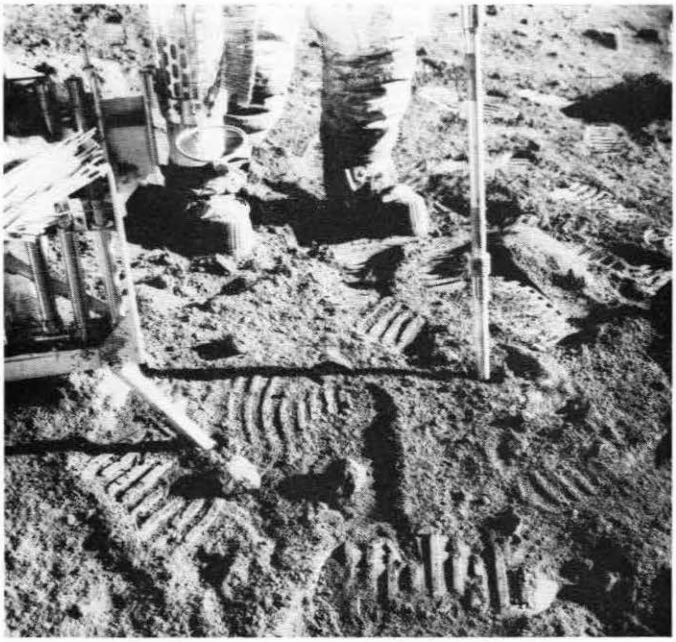


Fig. 8. Scoop pushed into surface in the vicinity of Bench crater. Depth of penetration is about 6 in. The hole remained open after entry of the scoop. Lunar soil is adhering to the legs of the astronaut's suit and to the lower right portion of the tool carrier

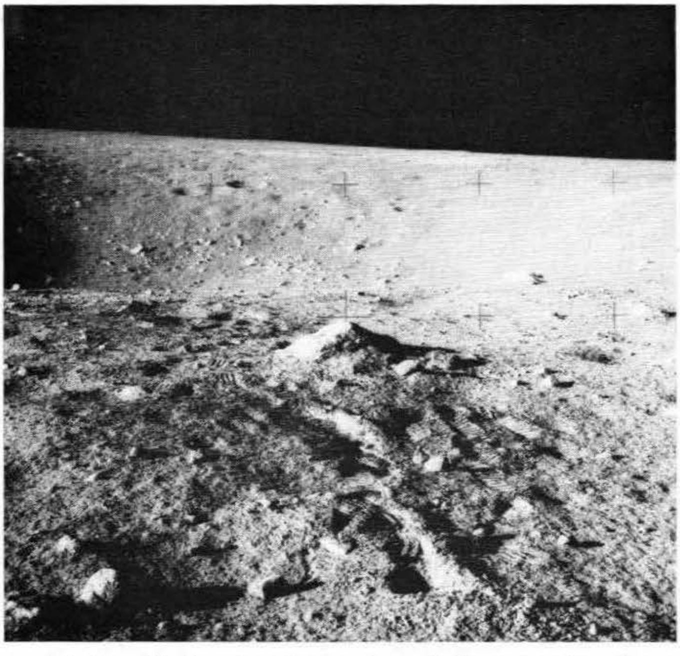


Fig. 9. Fillet material around partially exposed rock

footpad is shown in Fig. 2, and a penetration typical of the other footpads is shown in the photograph of the $+y$ footpad of Fig. 3. The depression adjacent to the pad and appearing below the bent contact probe in Fig. 3 was apparently not caused by an impact and bounce of the $+y$ footpad but is a natural surface crater. This is indicated by the track of the contact probe seen in the foreground of Fig. 3. It is evident in other photographs that this groove extends several feet to the left of Fig. 3, indicating the motion of the spacecraft in the last one or two seconds of descent. The position of the groove is consistent with the location of the contact probe on the footpad, and no other groove appears in a similar position with respect to the small crater in question. It was observed on the Apollo 11 landing that the effect of the exhaust gas of the descent engine is to accentuate the surface disturbance caused by a probe rather than to cover it up, so it is unlikely that a track was formed and subsequently obscured. The broken probes indicate that the spacecraft was travelling in a direction slightly north of west in the final stages of descent.

As in the Apollo 11 photographs, the surface under the descent engine and adjacent to the footpads (Fig. 3) appears to have been swept by the exhaust gas of the descent engine, although more particles seem to have been left on the surface in the vicinity of the Apollo 12 lunar module than under the previous spacecraft. This may have been due to the different shutdown conditions. In a number of pictures, such as Fig. 4 which shows an area of lunar surface about 40–50 ft to the east of the centre of the lunar module along its approach track, a path appears which is clearly different from the surrounding surface, and occurs apparently along the approach path. This path seems to be a result of the surface disturbance caused by the exhaust gas during descent. According to the descent trajectory the spacecraft's engine nozzle was 30–40 ft above the surface at a position corresponding to the right-hand edge of the area shown in Fig. 4.

OBSERVATIONS DURING EXTRA-VEHICULAR ACTIVITIES

While the lunar module was on the moon, Conrad and Bean made two separate excursions on the lunar surface, as shown in Fig. 1. The first of these was concerned primarily with setting out the various lunar surface experiments which had been carried on board the spacecraft, although soil and rock samples were collected. Travelling a distance of about one mile in the second extra-vehicular activity, the astronauts visited several sites of interest including the Surveyor III spacecraft, took many photographs, collected soil and rock specimens, drove core tubes into the lunar surface and removed portions of the Surveyor spacecraft.[1]

From the astronauts' activities during these journeys, information relating to the physical characteristics and the mechanical behaviour of the lunar surface material at the Apollo 12 landing site was extracted. The operations included

- (*a*) initial familiarization and adjustment to the lunar environment
- (*b*) trenching and collection of rock, soil and core tube samples
- (*c*) deployment of the solar wind composition experiment, the United States flag, and the Apollo lunar surface experiments package
- (*d*) observations and photography relating to the lunar module landing interaction with the lunar surface.

Characteristics of the surface materials

In general the surface material at the Apollo 12 site can be described as a medium-grey, slightly cohesive, granular soil that is composed largely of bulky grains in the silt to fine-sand

---

[1] A brief description of the tools carried by the astronauts is given in the Appendix.

size range, with scattered glassy rocks and coarse rock fragments. Large rock fragments ranging in size from several centimetres to several metres across and varying in shape from angular to subrounded are sparsely strewn throughout this matrix material. Coarse blocks occur abundantly on and around a few craters. Most of the rocks are partially buried with fillets of fine-grained material built up around them. The soil is generally similar in appearance and behaviour to that encountered at the Apollo 11 site and at the Surveyor equatorial landing sites. However, there is some variability in soil conditions at different points along the geologic traverse shown in Fig. 1, as well as some features and aspects of behaviour that are unlike those found at the Apollo 11 site.

Surface colour intensity was more variable than had been observed previously. Lighter and darker shades of grey were evident at different points. As was the case also at the Apollo 11 site, the surface took on an appearance which was browner than normal when viewed across the sun's direction.

The astronauts left darkened trails where they passed along the surface. This characteristic, which has yet to be ascribed specifically to either a change in texture or to a true colour difference between the undisturbed surface and the soil directly beneath, was also observed at the Apollo 11 and Surveyor sites.

The astronauts concluded that there were three different and distinct areas along the second walk in terms of soil texture and behaviour.

(*a*) In the vicinity of the lunar module and out to Head crater the soil is of moderate compactness and provides good support for the astronauts and experiment packages.

(*b*) In the vicinity of Sharp crater the soil was the softest. It could be easily trenched, as shown by Fig. 5, and footprints in this area were the deepest.

(*c*) In the Halo and Surveyor craters region, the soil was the firmest, according to the astronauts. In this area the soil had the appearance of a dusty surface that had been lightly rained upon, as may be seen in Fig. 6. The material was described as more cohesive and coarser than in other areas. The bootprint indicates that this material compacts under load in the same manner as the other types of surface material encountered.

No quantitative determination of different footprint depths from the photographs has been made yet. Colour variations were evident within small zones and the material did not appear to be homogeneous with depth at all locations.

In undisturbed areas the lunar surface exhibits bands of grooves about $\frac{1}{3}$ cm deep north-west of the lunar module and near the Middle Crescent crater north-west of Shelf crater at about 200 m from the lunar module. These bands were approximately 30 m wide and followed a north–south direction that was approximately normal to the direction of striations presumed to have been caused by the lunar module engine exhaust. Similar lines were also observed on the outer slopes of Sharp crater, near Halo crater, at and near the Surveyor III spacecraft. The lines in the Surveyor crater were parallel to the circumference of the crater. Near Surveyor they appeared to follow a north-west direction. They are unexplained.

Dust and adhesion

The tendency of the loose, powdery surface material to move easily when disturbed in the lunar vacuum and to travel along ballistic trajectories in the airless $\frac{1}{6}g$ environment imposed operational problems. These were augmented by the fact that the same material also exhibited adhesive characteristics so that the fine soil stuck to any object with which it came into contact. Consequently equipment and space suits became coated with lunar soil, and housekeeping problems developed from the dust brought aboard the lunar module at the conclusion of extra-vehicular activity periods.

Fine-grained material adhered to the astronauts' boots and space suits, the television cable, the lunar equipment conveyor, components of the lunar surface experiment package, astronaut tools, sample return containers, the colour chart and the cameras and camera magazines.

It was noted after departure from the moon, when the lunar module cabin pressure had been raised to 5 lb/sq. in. and zero gravity conditions prevailed, that dust previously adhering to different surfaces came free and floated about the interior of the capsule.

Conrad commented that camera magazines coated with lunar soil when stowed were apparently clean when removed from their bags in the command module a few days later. However, the lunar soil has still shown both adhesive and cohesive properties after some months under both dry nitrogen gas and atmospheric conditions. It is possible that the later cohesion arises from different chemical or physical mechanisms. The surface and interparticle forces responsible for the cohesive and adhesive properties of lunar soil have not yet been identified.

Cohesion

Disturbed surface material throughout the area covered possesses a small but significant amount of cohesion as shown in the photographs by retention of deformed shapes, footprints, clumping of disturbed material, near-vertical trench walls and the fact that the core tube sample holes remained open after withdrawal of the core tube. On the other hand this cohesion, at least when the soil is in the undisturbed state, cannot be great since the soil was kicked up easily, and the problem with dust was severe.

A photograph of a bootprint taken with the close-up stereo camera is shown in Fig. 7. It may be seen that the soil under and between the boot ribs has been compressed to form a coherent mass and that some of the individual grains can be distinguished. This photograph covers a surface area of about 9 sq. in., with a resolution of about 100 microns.

Figure 8 shows the scoop pushed into the surface in the vicinity of Bench crater to a depth of about 6 in. The open hole adjacent to the scoop handle is evidence of cohesion. Adhesion of fine material to the lower right corner of the tool carrier and to the legs of the astronaut's suit is also shown. Clumps of fine-grained material bulldozed away from the $-y$ pad as a result of the interaction between the lunar module and the lunar surface during landing are shown in Fig. 2.

Frictional characteristics

As at the Apollo 11 site, the lunar soil encountered during this mission derives a major portion of its strength from interparticle friction. This is shown by the fact that the material's resistance to deformation increases considerably with confinement. The relevant material properties can be assessed from the following observations.

(*a*) The penetrations of the lunar module footpads were small, in the range 1–2 in., except for the $-y$ footpad which penetrated (Fig. 2) to 4 in. These penetration values correspond to static bearing pressures of 0·8–1·1 lb/sq. in.

(*b*) The depth of penetration of the astronauts' boots on a level surface was small, of the order of ½ in., as seen in Fig. 9. However, softer spots were found on the rims and slopes of relatively fresh, small craters (Fig. 10).

As in the Apollo 11 mission, no special soil mechanics testing or sampling devices were included in the equipment carried on the Apollo 12 lunar module, and no other force or deformation-measuring device was used during the surface activities. Accordingly the strength and deformation characteristics of the lunar soil could be determined only by indirect means, such as from the observations described which were made on the appearance of the lunar material and the nature of its interaction with objects of known weight and geometry. From analyses based on such indirect means it appears that, although during the second extra-vehicular activity period the astronauts noted three distinct areas in terms of soil consistency, compaction and firmness, the mechanical behaviour of the soil is in general consistent with the behaviour that would be expected for a soil having properties characteristic of the soils studied at the Apollo 11 site (Costes *et al.*, 1969) and the Surveyor equatorial landing site (Scott and Roberson, 1968). Such a material has a density of the order of 1·5–2·0 gm/cu. cm, an angle of internal friction of 35–39° and a cohesion of 0·05–0·10 lb/sq. in. The unit bearing capacity is certainly considerably in excess of the pressure of 1–2 lb/sq. in. exerted by the astronauts and the lunar module footpads.

Although in the general area visited during the first extra-vehicular activity period many of the footprints appear to have resulted from soil compression, there were several instances in which footprints with portions 2–3 in. deep were accompanied by bulging of the surrounding surface. This type of soil deformation can be seen in the footprints near the rim of the crater shown in Fig. 10. Lateral soil bulging that accompanies imprinting or trenching action is also shown in Fig. 2 and it appears alongside the trenches dug by the contingency sampler. Such behaviour reflects deformation dominated by shear effects rather than by compression, and is consistent with the behaviour observed in some of the bearing tests conducted by the surface sampler during the Surveyor III and Surveyor VII missions (Scott and Roberson, 1968, 1969).

Reflecting these soil properties, the astronauts reported excellent mobility on the lunar surface during both extra-vehicular activity periods. Sinking was not excessive and no slippery surfaces were encountered. Walking caused compaction of the irregular surface of the soil underfoot. The photograph shows the soil to be packed into a dense state in which distinct grains are not visible (Fig. 7).

The astronauts decided not to go to the bottom of Bench crater because of the steepness of the walls. They experienced no difficulty on the walls of Surveyor crater (12° slope) and in fact they reported that the ground seemed firmer on the walls of this crater than elsewhere. However, there is evidence that the surface material on some crater walls may be of marginal stability. Fig. 11 is a view to the west into Sharp crater showing material that appears to have slid downslope. Crossing such zones could be hazardous. Distinct evidence of sliding was also observed by the astronauts in other craters.

Subsurface conditions

The granular surface material extends, at least, to the maximum depth probed by the astronauts. The astronauts reported little change in texture or consistency with depth, although observations in the lunar receiving laboratory suggest that some differences in grain size and colour with depth existed at the core tube sites. No difficulty was encountered by Conrad in scooping a contingency sample from a small crater in front of the lunar module, nor were there any problems reported in collecting selected soil samples in the area between the lunar surface experiment package deployment site, the east rim of the Middle Crescent crater and the lunar module.

Both the flagstaff and the solar wind composition experiment staff were pushed to depths comparable to the penetrations of the same staffs at the Apollo 11 site. From the distance above the surface of the knurled markings on the flagstaff (Costes *et al.*, 1969, Figs 4–8) the penetration of the flagstaff is estimated to have been approximately 7 in. From the distance above the surface of the knurled markings on the solar wind composition staff it was estimated to have penetrated to approximately 6 in. below the surface. Less difficulty was encountered in core tube driving in the immediate vicinity of the lunar module than at the Apollo 11 site.

A trench about 8 in. deep was dug near the rim of Sharp crater using the scoop. No difficulty was encountered in digging and the trench depth was limited only by the length of the extension handle. The trench remained open and stable, although the top edges could be

Fig. 10. Astronaut bootprints near small crater with soft rim

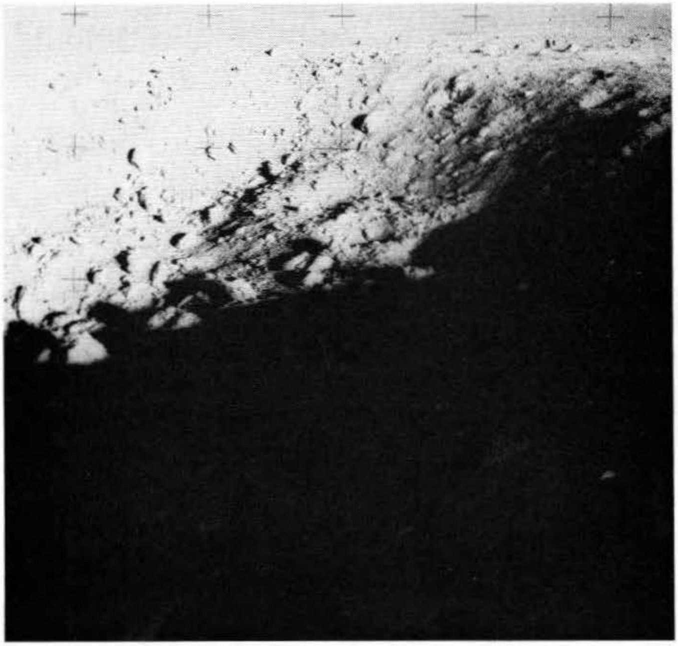


Fig. 11. Westward view into Sharp crater showing evidence of instability of unconsolidated surface material

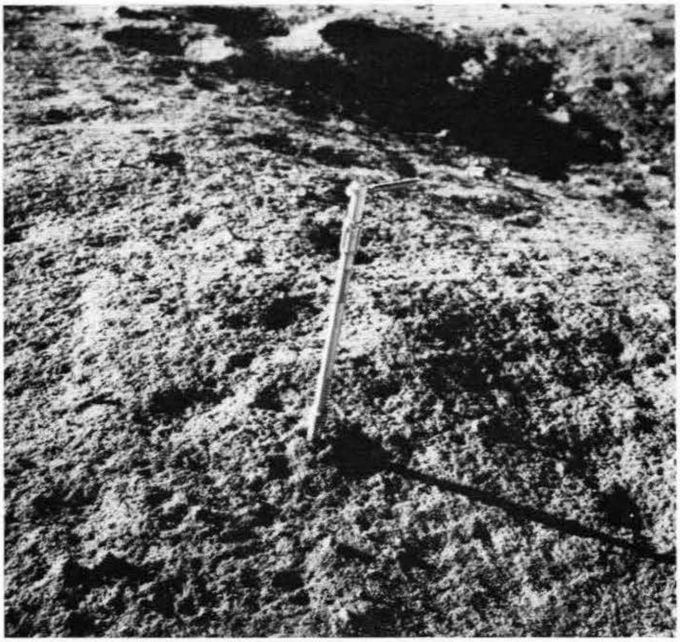


Fig. 12. Double core tube at the end of driving. Little disturbance of the surrounding surface is evident as a result of driving the sample tubes

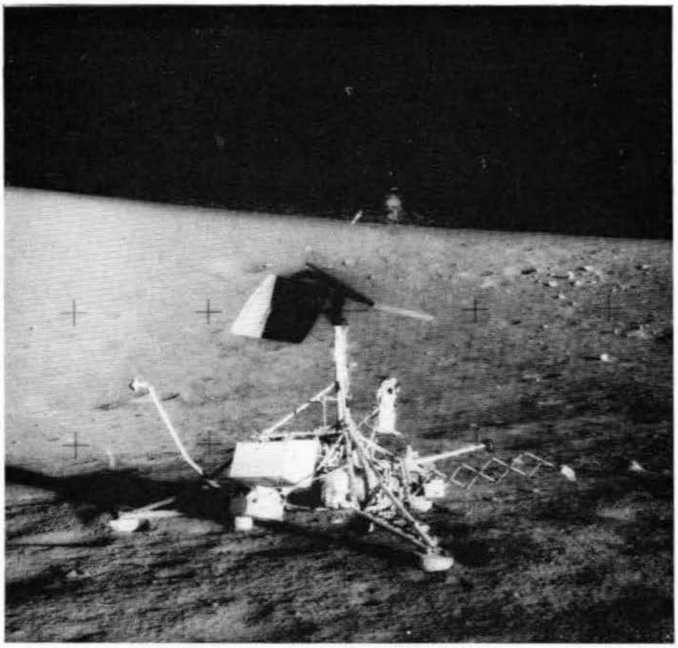


Fig. 13. Surveyor III with the lunar module in the background. Footpad 1 is to the left, footpad 2 in the foreground, and the surface sampler extends to the right

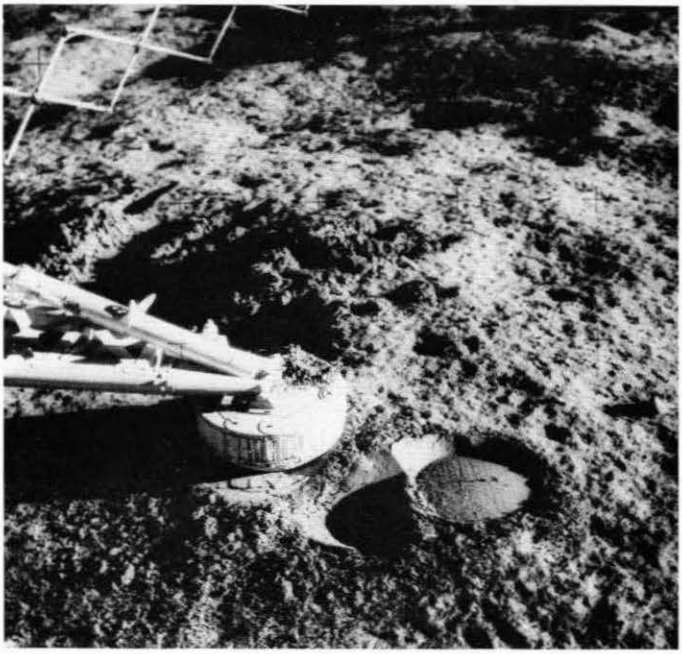


Fig. 14. Footpad 2 area of Surveyor III showing footprints formed during touchdown hop. Note fresh appearance of the footprints and waffle pattern caused by the footpad honeycomb

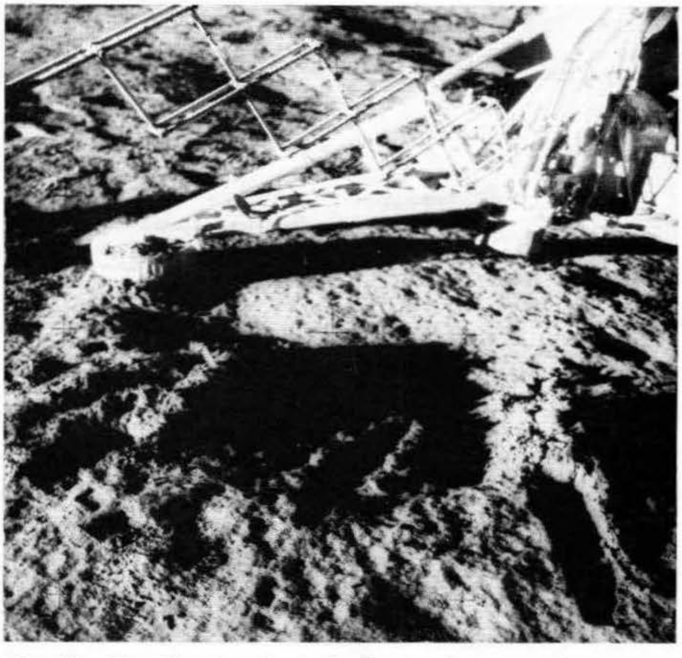


Fig. 15. Results of soil mechanics surface sampler operations, Surveyor III

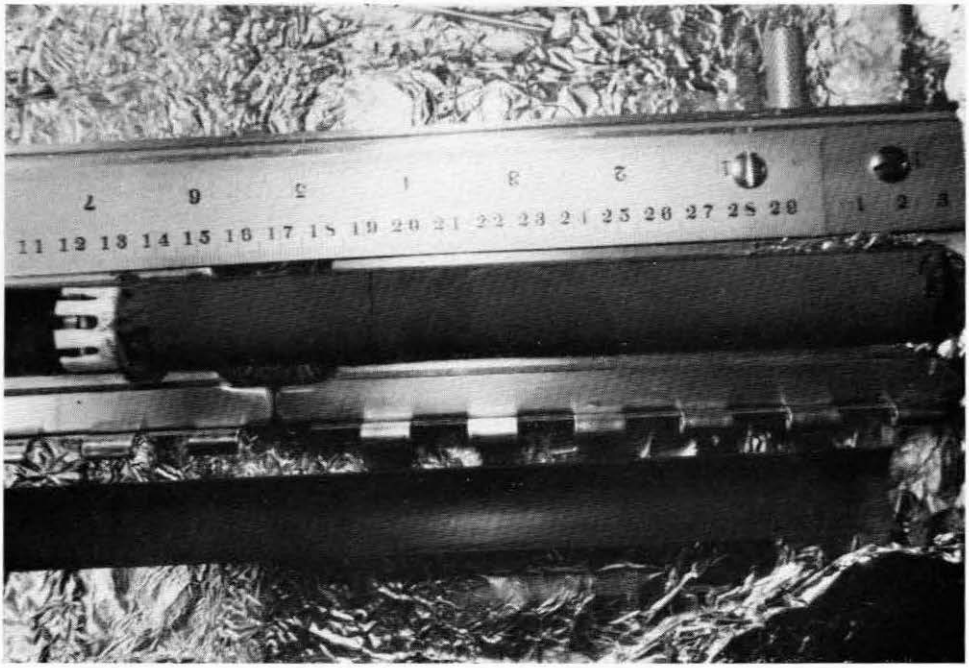
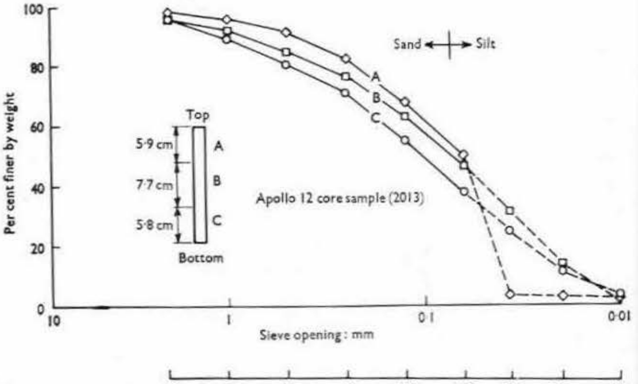


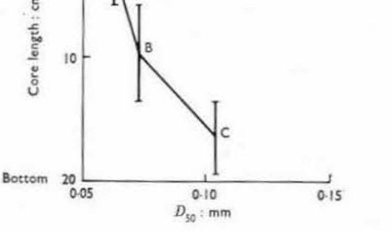
Fig. 16 (above). Core tube sample (2013) taken during first extravehicular activity. The circular feature is a reflection of the camera lens

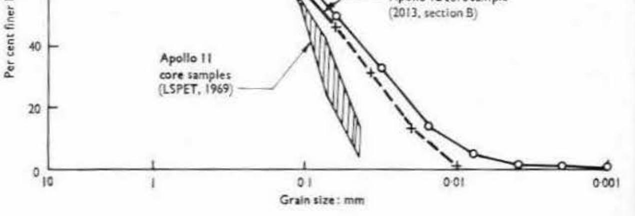
Fig. 17 (right). Sieve analysis of Apollo 12 core sample (2013)

Fig. 18 (below). Mean grain size plotted against depth in Apollo 12 core sample (2013)

Fig. 19 (below right). Comparison of results of sieve analyses from Apollo 11 (2007, 2008) and Apollo 12 (2013, section B) core samples







crumbled easily. Analysis shows that if the soil possesses a density, friction angle and cohesion of the magnitudes postulated, then vertical walls several times this height should remain stable.

A core tube was then driven without difficulty to its full length (35 cm) beneath the bottom of the trench. It was reported that this tube could have almost been pushed in without a hammer.

A double core tube was driven near Halo crater to a depth of about 70 cm. Fig. 12 is a view taken at the completion of driving. It may be seen that, except for some bulging, there is essentially no disturbance of the ground surface adjacent to the core tube. No hard material was encountered during the driving of any of the core tubes, and they were easily withdrawn from the ground in each case. The astronauts reported that the core tubes were augered between blows although they indicated it was probably not necessary; the influence of this on the samples brought back is not known. They also noted that the soil showed increasing resistance to penetration with depth. Core tube holes remained open after withdrawal of the tubes.

It is important to emphasize that the core tube bits used for Apollo missions 11 and 12 differed from each other. In view of the design difference and because no trenching at a point away from the lunar module was attempted at the Apollo 11 site, it would be unwise to draw conclusions about differences in soil consistency beneath the surface between the two locations.

Soil conditions at the Surveyor III site

Surveyor III with the lunar module in the background is shown in Fig. 13. Examination of the photographs taken at this site suggests that the ground surface has undergone little change in the past two and a half years. For example, Fig. 14 shows the waffle-textured print of footpad 2 even more clearly than the original Surveyor photographs. The detail shown indicates clearly that little change could have taken place and any depositional or erosional processes must be slow relative to two and a half years.

From other photographs it can be seen that footpad 1 left a waffle imprint similar to that of footpad 2. A more thorough examination of the astronauts' photographs of the Surveyor spacecraft shows that the spacecraft had moved about three inches between the last Surveyor operations and the time of the astronauts' visit. The movement appears to have been due to a sudden collapse of the gas-filled shock absorbers on the Surveyor legs 1 and 3. When this occurred some of the soil partially covering footpad 3 was displaced revealing a lighter coloured protected portion of the footpad surface. Footpad 1 was not visible and footpad 3 was only partially visible to the Surveyor television camera. The astronauts reported that the white portions of the Surveyor spacecraft were a light tan colour, and it appeared as if some of this coating were dust. The possibility that at least some of the coating was caused by blowing dust from the lunar module landing cannot be eliminated at present. Further studies of the pictures and possibly of the components brought back to Earth should clarify this.

A view of the area of surface sampler operations is shown in Fig. 15. Unfortunately the slope of the surface on which Surveyor III rests and the low sun angle at the time of the astronauts' visit have the result that much of the surface sampler test area is in shadow. However, the major features (trenches and some of the impact and bearing test points) are visible and a comparison with the Surveyor television pictures of the lunar surface details around impact test 1, for example, as seen in Fig. 15 in the left foreground is possible. In the preliminary examination no change in any identified surface feature has yet been detected.

EXAMINATION OF SAMPLES IN LUNAR RECEIVING LABORATORY

General description

Considerably less soil material was returned from the Apollo 12 mission than from Apollo 11. Total weight of the material with a grain size smaller than 2 mm is approximately 4 kg, as compared with 11 kg for Apollo 11. The small quantity from Apollo 12 complicates the comparison of the samples from the two landing sites. Nevertheless, most of the Apollo 12 soil samples are visually identical to the Apollo 11 soil, i.e. the soil is a charcoal grey with a slight brown tinge. A significant portion of the soil is finer than the unaided eye can distinguish. The soil adheres in a fine layer to everything that comes into contact with it, including stainless steel tools, Teflon bags and rubber gloves.

The first core tube sample to be opened and examined in the lunar receiving laboratory nitrogen cabinets was the core taken during the first extra-vehicular activity in the vicinity of the lunar module (see Fig. 1). This sample (2013) was similar in appearance to the two core tube samples taken during the Apollo 11 mission (2007 and 2008). As before, the sample was uniform medium grey to medium-dark grey in colour and no individual particles were visible. Fine reflecting surfaces were present over about 10% of the area which gave it a slightly sparkly appearance. The sample retained its cylindrical shape while resting in a horizontal trough, thereby indicating that the soil retained some cohesion (see Fig. 16). Probing the sample with a spatula showed that the fine particles tended to form clumps up to half a centimetre in size; a vertical face one centimetre high could be cut across the diameter of the sample. There were transverse cracks across the sample which might indicate different zones within the lunar soil sample depth (three sections were found to have slightly different grain size distributions). Alternatively, the cracks may have been due to the rotation of the core tube while the astronaut was taking the sample on the lunar surface.

Some Apollo 12 samples were different from any obtained during the Apollo 11 extra-vehicular activity. Documented sample 5D (12033), taken in a trench dug in the north-west quadrant of Head crater (see Fig. 1), has a distinctly different colour from the other soil samples in that it is light grey, similar to the colour of cement. In addition, the bottom half of the double core tube (2012) contains zones of different colour and grain size, including one distinct zone approximately 1 in. long consisting primarily of sand-sized and larger particles.

Sieve analysis

Half of the first core tube sample (2013) was removed along the length of the core in three sections defined by two of the transverse cracks described. These sections were sieved individually and the results are shown in Fig. 17. A, B and C refer to the upper, middle and lower sections of the core, respectively. The curves are shown as dashed for the material finer than a no. 230 sieve (0·063 mm) because below this size they may be considerably in error due to very fine particles sticking together in clumps or adhering to larger particles. Curve A is particularly suspicious below the no. 230 sieve, because of the sudden break in the distribution. Unfortunately, it was impossible to check the results as the samples had already been given to biologists to expose to the various plants and animals in the lunar receiving laboratory.

It is interesting to note that the grain size increases with depth in the core sample. The mean grain size D_{50} (i.e. the sieve opening at which 50% of the soil is finer by weight) is plotted against depth in Fig. 18. It will not be known until more detailed studies are performed whether this increase in grain size is gradual or occurs in discrete steps, indicating zones in the lunar soil.

Figure 19 compares the grain size distribution of the Apollo 12 core sample with that obtained for the Apollo 11 core samples analysed by the lunar sample preliminary examination team (LSPET, 1969). Only section B of the Apollo 12 core is shown as it represents roughly the average distribution for the entire sample. It can be seen that the distributions are nearly the same for grain sizes larger than about 0·1 mm. Below this the distributions differ significantly, with the Apollo 12 analysis indicating a larger proportion of silt-sized particles. However, it should be pointed out that improvements in the sieving equipment have been made since the Apollo 11 analysis. Thus the apparent variation is not sufficient evidence to indicate a distinct difference between the two soils. In any case, accurate plots for the grain size distribution below the no. 230 sieve must await the results of the principal investigators.

Bulk density

The bulk densities of the Apollo 11 and 12 core tube samples are presented in Table 2.

A note of explanation is required concerning the range of diameters shown. A small error in the measured diameter of the sample produces a large error in the calculated sample volume and the bulk density. The Apollo 11 core densities reported previously by the preliminary examination team (LSPET, 1969) were based on a nominal diameter of 2·00 cm; however, the drawing of the Apollo 11 core bit in Fig. 20 indicates that the diameter may be taken to be 1·95 or 1·97 cm. The same is true for the Apollo 12 core bit, shown in Fig. 20. Thus the bulk densities shown in Table 2 have been calculated for a diameter of 1·97.

The in situ bulk density of the lunar soil has been of great interest (Scott, 1968; Jaffe, 1969). Unfortunately the Apollo 11 core samples could not provide an answer because of the shape of the bit which was designed some years previously by members of the Apollo geological team without reference to soil mechanics considerations. From Fig. 20 it can be seen that the Apollo 11 bit tapers inwards from a diameter of 2·92 cm to 1·95 cm; these diameters correspond to areas of 6·7 and 3·0 sq. cm respectively. Thus if the soil were very porous, it could be argued that the bit would compress the in situ soil during sampling to as much as double its original density. Conversely, if the soil were densely packed, the shape of the bit would deform the soil and cause it to expand to a lower density. Thus the bulk densities measured in the Apollo 11 cores could indicate an in situ density from a value of 0·75 gm/cu. cm to a value in excess of 1·75 gm/cu. cm.

The Apollo 12 core tube bit is far from optimal in design but results in a smaller range of uncertainty. On the other hand, hammering a core into the soil is known to cause more disturbance to the sample than if the core were pushed into the ground at a high and constant

Table 2. Data from the core tube sample

Core tube serial number	Weight of sample, gm	Length of sample, cm	Bulk density,* gm/cu. cm	Total length of sample,† cm	Depth of core tube,‡ cm	Core recovery,§ %
Apollo 11						
2007	52·0	10·0	1·71	11·8	>25	<47%
2008	65·1	13·5	1·59	15·3	<32	>48%
Apollo 12						
2011	—	17·4‖	—	18·5	~37	~50%
Double 2010 (upper)	56·1	9·3	1·98	42·2	69	61%
Double 2012 (lower)	189·6	31·8	1·96			
2013	102·9	19·4	1·74	20·5	37	56%

* Based on a sample diameter of 1·97 cm.

† Adjusted to include the length of the discarded bit sample: for Apollo 11, an additional 1·82 cm; for Apollo 12, 1·09 cm.

‡ Determined from mission photography.

§ Total length of sample/depth of core tube.

‖ This core tube has not been opened but has been kept in storage in the lunar receiving laboratory. The sample length was determined by means of X-radiography of the core tube.

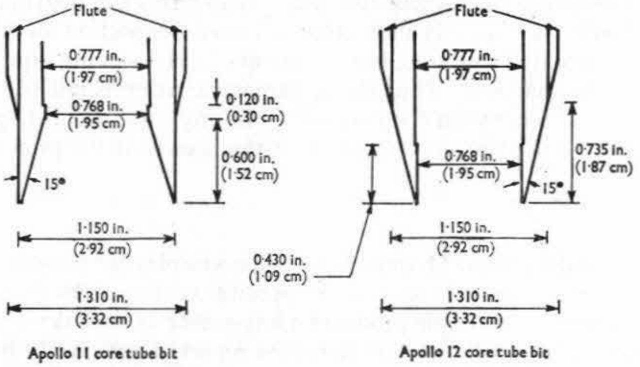


Fig. 20. Comparison of Apollo 11 and 12 core tube bits

speed (Terzaghi and Peck, 1948). For the time being the hammering method is unavoidable and it is necessary to estimate disturbance in terms of the dimensions of the core tube. The degree of sample disturbance has been found to be dependent on the area ratio A_r defined as

$$A_r(\%) = 100 \frac{D_e^2 - D_i^2}{D_i^2}$$

where D_e is the external diameter and D_i is the internal diameter. The smaller the value of A_r, the less disturbed is the sample (Hvorslev, 1949).

The core bits have raised flutes (shown in Fig. 20) to facilitate their removal by the astronaut after the sampling operations. Using a weighted average for D_e to include the effect of the flutes, A_r for the Apollo 12 core tubes is

$$A_r = 100 \frac{(3{\cdot}06)^2 - (1{\cdot}97)^2}{(1{\cdot}97)^2} = 141\%$$

In terrestrial terms this would be considered very poor, as a standard two inch sampler has an area ratio of only 14%. Nevertheless, it is a considerable improvement over the reverse-flare core bit of Apollo 11.

It is also important that the area of the bit at the cutting edge is slightly less than the area inside the tube to reduce the friction between the core sample and the inside walls of the core tube. For the Apollo 12 bit the difference between the two areas is 2%, which is appropriate, although the change could be more gradual rather than abrupt.

Taking these considerations into account it is felt that a rough estimate can be made of the average bulk density of the top 30 cm of the lunar surface at the Apollo 12 landing site. Based on the measured bulk densities in the core tubes, the in situ bulk density is approximately $1{\cdot}8 \pm 0{\cdot}2$ gm/cu. cm.

In the single core tube 2013 and the double core tube of Apollo 12 the percentages of core recovered were about 65 and 60% respectively. The depth to which the two single cores of Apollo 11 were driven is not known closely enough to enable a meaningful recovery ratio to be calculated.

DISCUSSION

One of the questions which arises in discussions of lunar exploration is the efficacy of unmanned spacecraft in returning information on the nature of the lunar environment. It is interesting therefore to compare the estimates of lunar material properties obtained from the operations of the Surveyor spacecraft series with the results of measurements made on the Apollo samples brought back to Earth. Data were returned from the 600 lb (Earth weight) Surveyor vehicles by radio signals only. Six hundred line television pictures of the lunar surface were obtained by this means, as well as telemetry data on the chemical composition and mechanical properties of the lunar surface through the use of specially designed experimental apparatus. Besides these experiments the engineering measurements made in the course of landing and operation of the spacecraft on the lunar surface were analysed and interpreted by specialized teams of experimenters. The engineering data from the radar system during descent, the strain gauges on the legs during the landing impact and from temperature-sensing devices in various electronic compartments after landing were all processed.

The interpretation of the lunar surface chemical composition from the comparatively simple chemical analysis experiment has been remarkably accurate (LSPET, 1969). From the mechanical properties experiment soil property values were obtained; as already discussed and shown by Costes *et al.* (1969) the observations of the soil behaviour at the two Apollo landing sites have indicated behaviour consistent with these numerical values. In fact the Surveyor surface sampler tests remain the sole source of quantitative data about the soil mechanics properties of the lunar surface.

When focused on the lunar surface at closest approach, the highest resolution of the Surveyor television camera was about $\frac{1}{4}$–$\frac{1}{2}$ mm (250–500 μ). By a variety of techniques, including counting resolvable particles down to this size (Shoemaker and Morris, 1968), observing features of a visible footpad imprint on the lunar surface (Christensen *et al.*, 1968) and horizon lighting effects after lunar sunset (O'Keefe *et al.*, 1968), several estimates of the lunar surface grain size distribution were made from the Surveyor observations. These generally agreed that the material was fine-grained in the silty fine sand or fine sandy silt size range with about 90–95% of the material finer than 1 mm in size, and about 50% of it finer than the size range of 20–100 μ. In engineering applications these estimates were used in planning and simulation studies for the Apollo missions. It can be seen by comparison of the Apollo 11 and 12 results of Figs 17 and 19 that the estimates were in the correct size range. The mechanical properties of a number of simulant materials in this size range are very similar to those of the real lunar soil, although the physico-chemical bases for the properties are different. In particular the small but significant (for objects a few inches in diameter under lunar gravity) amount of cohesion in lunar soil may be due to van der Waals or electrostatic forces between the grains. In a terrestrial soil of the same grain size range, this cohesion can readily be simulated by damping the material slightly.

From the results of the unmanned landings it was predicted that the 20 000 lb (Earth weight) lunar module would be able to land safely on a relatively level surface with only a small penetration of the footpads into the lunar soil for a given descent profile. It was also concluded that the astronauts would not sink deeply into the lunar soil and that they would be able to move about freely from a surface traction point of view. Prior estimates were also made of the ability of various tools to penetrate the surface. Fortunately the lunar surface has retained the homogeneity indicated by the Surveyor tests, and these forecasts have proved to be accurate. The feasibility of manned landings, lunar surface operations and departures has been shown. Although consideration was given to the problem of lunar dust adhesion in the Surveyor findings, this appears to have caused more trouble than expected as a result of the mobility of the soil in the lunar environment.

The emphasis in the first landings has been on performing scientific experiments and returning soil and rock samples for chemical analyses and dating. It has not yet been possible to carry out specifically mechanical tests on the lunar surface or to obtain a sufficient quantity of lunar soil to permit a laboratory test programme on soil mechanics properties to be initiated. Instead the results reported in this Paper and by Costes *et al.* (1969) have been by-products of the successful flights. Satisfactory testing of the lunar soil, either on the moon or in the form of samples brought back, will not be easy. In the former case the operational constraints make it difficult to devise adequate testing equipment, and in the latter the probable sensitivity of the lunar soil to the inevitable disturbance and change in atmospheric conditions render any test results problematic. The necessity of returning, handling and testing the soil in as high a vacuum as possible imposes restrictions on the design of laboratory test equipment.

APPENDIX—APOLLO LUNAR HAND TOOLS

Astronauts are supplied with a set of tools and a tool carrier for use on the lunar surface. The tools are designed primarily to facilitate the retrieval and storage of geological specimens of lunar rocks and soil. A brief description of the equipment is given for background information.

The core tubes (Fig. 12) are approximately 15 in. long, 1 in. in diameter and are made of aluminium. Each tube is fitted with a cutting edge which is removed after sampling and replaced with a screw-on cap. Inside the tube is a piston-like device to help retain the soil after sampling (Fig. 16). At its upper end the core tube can be attached to a universal extension handle (Figs 8 and 12) which is designed to be used with several tools so that the astronauts do not have to kneel or bend down. The latter movements are difficult with the present design of pressurized space suit. The extension handle is 24 in. long, 1 in. in diameter and is fitted with a stainless steel anvil at the upper end so that a hammer may be used for driving purposes. The hammer itself is similar to a standard geological hammer but with a handle adapted to the astronauts' grasp.

Two scoops, one large and one small, are provided for the retrieval of surface specimens and may be attached to the extension handle. A pair of spring-loaded sampling tongs 26½ in. long can be used to pick up surface rocks of diameters ranging from ⅜–2½ in. An instrument staff one inch in diameter to provide support for photography and a contingency sampler which is used to obtain a first sample quickly in case of an emergency departure complete the tool kit.

The tools, together with Teflon bags to hold the collected soil and rock samples, are stored on a three-legged tool carrier which is shown in Fig. 8. To help establish the vertical in the weak lunar gravity, a gnomon is carried; this is shown in Fig. 6.

A number of other devices also contact the lunar soil in the course of surface operations. Among those whose penetration behaviour was examined for this Paper were the flagstaff, an open-ended aluminium tube of ⅞ in. outer diameter and 0·035 in. wall thickness, and the solar wind composition experiment staff which was 1·3 in. in diameter.

REFERENCES

Christensen, E. M. *et al.* (1968). Lunar surface mechanical properties at the landing site of Surveyor III. *J. Geophys. Res.* **73**, No. 12, 4081–4094.

Costes, N. C., Carrier, W. D., Mitchell, J. K. & Scott, R. F. (1969). Apollo 11 soil mechanics investigation. Preliminary science report, NASA SP-214, pp. 85–122.

Duke, M. B., Woo, C. C., Bird, M. L., Sellars, G. A. and Finkelman, R. B. (1970). Lunar soil: size distribution and mineralogical constituents. *Science, N.Y.* **167**, No. 3918, 648–650.

Hvorslev, M. J. (1949). *Subsurface exploration and sampling of soils for civil engineering purposes.* Waterways Experiment Station, Vicksburg, Miss.

Jaffe, L. D. (1969). Lunar surface material: spacecraft measurements of density and strength. *Science, N.Y.* **164**, No. 3887, 1515–1516.

Lunar Sample Preliminary Examination Team (1969). Preliminary examination of lunar samples from Apollo 11. *Science, N.Y.* **165**, No. 3899, 1211–1227.

O'Keefe, J. A., Adams, J. B., Gault, D. E., Green, J., Kuiper, G. P., Masursky, H., Phinney, R. A., & Shoemaker, E. M. (1968). Theory and processes relating to the lunar maria from the Surveyor experiments. Surveyor VI mission report, Part II, Jet Propulsion Laboratory TR 32–1262, pp. 171–176.

Scott, R. F. (1968). The density of the lunar surface soil. *J. Geophys. Res.* **73**, No. 16, 5469–5471.

Scott, R. F. & Ko, H. Y. (1968). Transient rocket-engine gas flow in soil. *J. Am. Inst. Aeron. Astro.* **6**, 258–264.

Scott, R. F. & Roberson, F. I. (1968). Soil mechanics surface sampler: lunar surface tests, results and analyses. *J. Geophys. Res.* **73**, No. 12, 4045–4080.

Scott, R. F. & Roberson, F. I. (1969). Soil mechanics surface sampler (Surveyor VII). *J. Geophys. Res.* **74**, No. 25, 6175–6214.

Shoemaker, E. M. & Morris, E. C. (1968). Size-frequency distribution of fragmental debris. Surveyor Project Final Report, Part II, Jet Propulsion Laboratory, TR 32-1265, pp. 86–102.

Terzaghi, K. & Peck, R. B. (1948). *Soil mechanics in engineering practice.* New York: Wiley.