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APOLLO PROGRAM SOIL MECHANICS EXPERIMENT:

FINAL REPORT

by

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INTRODUCTION

The Apollo lunar landing missions provided the first opportunity for direct collection of data relating to the physical characteristics and mechanical behavior of the surface materials of an extraterrestrial body by other than remote means. The acquisition of such information from the first manned lunar landings was needed to aid in accomplishing the following broad objectives:

1. To provide engineering data on the interaction of man and equipment with the lunar surface, thereby aiding in the evaluation of the Apollo missions, and in the planning of future lunar surface scientific investigations and related engineering tasks supporting these activities.

2. To enhance the scientific understanding of the nature and origin of lunar surface materials, and the mechanisms and processes responsible for the present morphology and consistence of the lunar surface.

To achieve these objectives a Soil Mechanics Investigation was included in the scientific experiments planned for the Apollo missions, and the investigating team,* was charged with the responsibility for the systematic acquisition and analysis of lunar soil mechanics data.

The Soil Mechanics Investigation had the following engineering objectives:

1. To obtain information relating to the landing interaction of the Lunar Module (LM) with the lunar surface, and lunar soil erosion caused by the spacecraft engine exhaust.

2. To provide a basis for altering mission plans because of unexpected conditions.

3. To assess the effect of lunar soil properties on astronaut and surface vehicle mobility.

4. To obtain at least qualitative information needed for the deployment, installation, operation, and maintenance of scientific and engineering equipment to be used in lunar exploration.

The writer was generally charged with that portion of the investigation related to the first objective, but contributed to all aspects of the soil mechanics investigation.

Specific scientific objectives of the Soil Mechanics Investigation included the following:

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*The team was composed basically of W. D. Carrier, III., N. C. Costes, J. K. Mitchell, and R. F. Scott. For various individual missions, they were assisted by W. N. Houston, L. G. Bromwell, H. J. Hovland, H. T. Durgunoglu, and D. D. Treadwell. Costes was Team Leader on Apollo 11, Scott on Apollo 12, and Mitchell on subsequent missions.

1. To verify lunar soil models previously formulated from earth-based observations and laboratory investigations, lunar orbiting and unmanned lunar landing missions.

2. To determine the extent of variability in lunar soil properties with depth and lateral position.

3. To assist in the interpretation of geological observations, sampling, and general documentation of maria features.

This report summarizes the results obtained by study of LM landing performance on each Apollo mission, with respect to the first objective above. The investigative effort was authorized under Contract NAS 9-11454.

KNOWLEDGE OF LUNAR SURFACE PROPERTIES PRIOR TO APOLLO 11

No attempt is made herein to give a complete review of the state of knowledge of the mechanical properties of the lunar surface as they were understood before the Apollo 11 lunar landing.

There is a variety of sources of preflight information, including ground-based visual, thermal, radio and radar measurements, the lunar surface photographs obtained by the United States Ranger and Orbiter spacecraft, and the first estimates of the lunar surface properties derived from the five soft landings of the United States Surveyor spacecraft series and from the landing of the Soviet spacecraft Luna 9 and Luna 13.

Generally, earlier deductions of the physical properties of the lunar surface based on terrestrial observations gave results different from those obtained by direct measurements from spacecraft. Therefore, only the latter will be summarized herein.

The results of the Surveyor spacecraft tests and analyses led to a lunar soil model of an essentially incompressible, slightly cohesive soil largely composed of grains in the silt to fine-sand size range.[1] The lunar soil behaved as do terrestrial soils with a porosity in the range of 35 to 45 percent, and a density of around 1.5 g per cubic centimeter. A cohesion of about 0.1 psi and a friction angle of 35 to 37 degrees in the normal pressure range of a few pounds per square inch satisfactorily represents the mechanical observations made to a depth of several inches in the lunar material. Where the soil extends to depths greater than several inches, some increase in strength with depth was observed. In places the soil may overlie rock fragments at a depth of inches or less. Lunar surface soil mechanics results from a variety of sources have been summarized in detail by Jaffe,[2] Scott,[3] and by Mitchell, et al.[4,5]

On the basis of the aforementioned deductions soil models were postulated and used for a number of calculations related to the descent and landing of the LM on the surface. Computations concerned with the dynamics of the landing[6] showed that LM footpad penetrations of 4 to 6 inches would be expected in a simultaneous four-point touchdown at a vertical downward velocity of 3 feet per second and zero lateral velocity, if the lunar soil extended to a depth of one or two times the footpad diameter, i.e., 3 to 6 feet.

The effect of the descent engine exhaust on the soil surface has been studied from a number of viewpoints. For the soil model postulated, but assuming the soil to be essentially impervious to gas flow, Hutton[7] found that during a vertical descent to the surface, erosion would begin when the exit plane of the nozzle was about 25 feet above the surface, and that the final erosional crater developed beneath the engine after landing and shutdown following a vertical descent would be of the order of 3 to 4 inches deep and 10 to 15 feet in diameter. The effect of the blowing surface material on visibility from the LM was also examined, and it was concluded that visibility would be somewhat impaired.

Considering the lunar soil to be a medium permeable to gas flow, Scott and Ko[8] examined the mechanics of compressible gas flow through the soil medium under lunar surface conditions. They found that gas could be stored under pressure in the soil's pores during engine firing. Thus engine shutdown could be followed by venting of the gas through the surface soil accompanied by upward ejection of the surface soil. The extent and amount of soil removed by such explosive outgassing depend, for a given soil and engine, considerably on the flight path and the engine shutdown pressure transients. A slow vertical descent and rapid decay at shutdown give the largest quantity of ejected soil material. Calculations of the magnitude of this effect require knowledge of the flight path of each spacecraft.

Calculations based on the lunar soil model adopted indicated that the astronauts' boots should not sink more than approximately 1 to 2 inches into the lunar surface during lunar surface activities if the soil extended to a depth of inches to feet. Traction was anticipated to be good. No difficulties in obtaining surface soil samples, driving core tubes or installing staffs in the ground were expected if sufficient soil depth were present. Mobility problems might be expected only in trying to descend or ascend crater walls at angles greater than perhaps 15 degrees.

INVESTIGATION PLANNING AND IMPLEMENTATION

Data Sources. Because the Soil Mechanics Investigation was included at a late phase of the Apollo mission planning, no special soil mechanics testing or sampling devices could be added to the hardware already fabricated for the first four missions. Accordingly, the main sources from which soil mechanics data could be extracted were as follow:

1. Real-time astronaut observations, descriptions, and comments.

2. Television coverage of the astronaut activities on the lunar surface. (Astronaut activity outside the LM on the lunar surface is referred to as extravehicular activity or EVA.)

3. Sequence camera, still camera, and close-up stereo camera photography.

4. Spacecraft flight mechanics telemetry data.

5. Interactions between various objects of known geometry and weight and the lunar surface, such as: (a) The Lunar Module, (b) The Astronauts, (c) The Early Apollo Scientific Experiments Package (EASEP) Instrument Units.

6. The Apollo Lunar Hand Tools (ALHT).

7. Various poles and shafts which were inserted into the lunar surface in the course of the extravehicular activities, including a contingency sampler handle, the Solar Wind Composition Experiment staff, a flagpole, and core tubes.

8. Astronaut debriefings.

9. Preliminary examination of earth-returned lunar soil and rock samples at the Lunar Receiving Laboratory.

A Self-Recording Penetrameter (SRP) for the soil mechanics experiment was designed for astronaut use and was employed on Apollo Missions 15 and 16.

<u>Preflight Activities</u>. Prior to each mission, detailed requirements were defined relative to spacecraft telemetry measurements, astronaut logs or voice records, lunar surface photography, and postmission participation in the preliminary examination of earth-returned lunar soil samples and astronaut debriefings. Emphasis was on simple astronaut tasks and observations that could yield meaningful soil mechanics information. Because of the heavy astronaut training schedule, only 1 hour of classroom lecture time was available for instructing each crew in basic lunar soil behavior. This was effectively increased for the 15th and 16th missions by the necessity for training those astronauts in the use of the SRP.

Parallel with these activities, simulation studies were performed on simulated lunar soil having similar physical and mechanical characteristics to those indicated by the Surveyor results.[9, 5, 10] Interences were made regarding material behavior during the lunar surface extravehicular activities taking into account the effect of lunar gravity.

Inflight and Postmission Activities. During the descent to the lunar surface, the lunar surface extravehicular activities, and the subsequent liftoff from the lunar surface, a variety of data became available in real time. These data provided the basis for a preliminary assessment of the physical and mechanical properties of lunar surface materials and a comparison with lunar soil models previously formulated from lunar orbital and unmanned landing missions and terrestrial simulations.

Upon the return of the crew to earth, a considerable amount of additional information relating to the Soil Mechanics Investigation became available from photographs, crew debriefings, and sample examination in the Lunar Receiving Laboratory.

In this report, results of the portion of the Soil Mechanics Investigation relating to objective 1, obtaining information on the landing interaction of the Lunar Module (LM) with the lunar surface will be summarized by mission.

APOLLO 11

Terminal States of Descent and Touchdown

Erosion and Visibility. The observations of exhaust gas erosion and footpad penetrations can be interpreted in the light of a variable Surveyor model soil profile and the motion of the lunar module during the terminal stages of descent.

From spacecraft telemetry the altitude of the LM was obtained and plotted as a function of time. The descent engine seems to have been shut down about 1 second after touchdown. Just prior to touchdown the spacecraft had a relatively low vertical velocity of about 1 feet per second and a high lateral velocity of about 3 feet per second, compared to preflight calculated values of 3 and 0 feet per second, respectively. From the telemetry and the pictures of the footpads and contact probes following touchdown, it appeared that the lateral velocity was to the spacecraft's left or in the -Y direction slightly east of south. At the time of the lunar surface photography the sun was due east at an elevation of about 12 degrees.

During descent an astronaut commented that some dust began to be picked up at an altitude of about 40 feet. During the scientific debriefing, Armstrong qualified the inflight remark by observing that he noticed "substantial haziness" at about 100 feet, although Aldrin said he first "saw evidence of disturbed material at about 240 feet." It appears from these remarks that the first observations of surface erosion were made with the footpads at an altitude of perhaps 230 to 90 feet above the surface (the altimeter records 10 feet when the spacecraft is on the surface). From the sequence camera movie the first visible surface soil disturbance occurred when the spacecraft was moving across a crater on the flight path. From the telemetry and the sequence movie frame, the spacecraft's altitude above the crater was about 100 feet. The height at which erosion first became noticeable was therefore higher than the predicted height of 25 feet at which this should occur based on the lunar soil model. It is possible that the material being moved was a surface layer of lower strength than the underlying layer (and the model soil), unless the initial erosion was strongly affected by the crater geometry. However, the observation would appear to indicate that even the surface material is cohesive, because a cohesionless soil of the same size range would be moved under the effect of the exhaust gas with the LM at a much greater elevation.

From the movie the descent was stopped for about 10 seconds when the footpads were 7 feet above the lunar surface. Soil transport by the LM descent engine exhaust was quite fully developed, and, except for the interruptions in the flow caused by occasional rocks, the surface was obscured. Armstrong in the post-flight debriefing noted some difficulty in obtaining a visual reference for the lateral control of the spacecraft motion because of the high velocity at which the particles were moving.

It is obvious, that erosion effects, probably, and the eroded soil, certainly, extended to great distances. In the scientific debriefing, the astronauts observed that the eroded material went a long way, and even obscured their horizon.

The relatively high lateral velocity of the spacecraft in the few seconds before touchdown means that erosion was never developed at one place as fully as would occur under vertical descent conditions. However, an analysis of shadow lengths in photographs, estimation of landing-leg shock absorber stroking at touchdown, and the observed footpad penetrations of 1 to 3 inches suggest that 4 to 6 inches of material may have been eroded. The lunar surface may not, however, have been level at this location before the landing.

It is apparent from photographs in the vicinity of the nozzle that some soil must have been removed by the exhaust gas. This is supported by the relatively small astronaut footprint depths in the immediate vicinity of the LM. Farther away the penetration of the boots was greater, as will be described later in this paper.

The Surveyor spacecraft landings demonstrated that the lunar surface is lighter colored than the underlying soil. Thus any disturbance of the surface is manifested by a dark appearance of the disturbed area. Some visible surface disturbance by the descent engine exhaust in terms of this effect was noted by the astronauts.

The combination of the lateral component of the spacecraft's velocity in the few seconds prior to touchdown and the engine shutdown transient probably gave rise to very little pressurizing of the soil by the exhaust gas in any one area. Post-shutdown gas venting effects from the soil would therefore be expected to be minimal.

For the approximate Apollo 11 descent profile, a diffused gas flow calculation was performed for the Surveyor model soil. The results of the computations indicate that engine gas flow penetrates the soil to a depth of approximately 5 to 7 feet under the engine, and extends laterally to the vicinity of the footpads. A region of soil about 7 feet in diameter and 3 or 4 inches deep centered under the engine is indicated to be of marginal stability following engine shutdown. If the soil possessed no cohesion, this region would have been ejected on shutdown. Because the soil is cohesive, the outward flow of exhaust gas would probably result in fracturing of the surface material.

Examination of the sequence camera movie suggests a change in the erosion pattern at about the engine shutdown time, although there is difficulty in correlating events on the movie with spacecraft events such as engine shutdown. This transient effect may be either due to some change in the engine behavior, or to an outgassing effect. In one photograph of the area below the nozzle there appears a number of fractures in the surface in the area certainly disturbed by engine exhaust. It is not possible at this time to reach definite conclusions about outgassing phenomena.

During ascent from the lunar surface the descent stage was left behind, so that the ascent engine exhaust impinged on it first. Soil erosion was, therefore, minimized until the ascent stage reached an altitude such that some of the exhaust could strike the lunar surface. Apparently little or no erosion took place during the ascent, as evidenced by the postflight remarks of the astronauts. The solar panels and dust sensor of the passive seismic experiment equipment, situated about 60 feet from the LM showed no signs of degradation from lunar soil blown out during the ascent.

Touchdown and Penetration. The low vertical and high lateral velocity of the LM at touchdown resulted in lower penetrations of the footpads into the lunar surface, and less stroking of the shock absorbers, then would be expected for a landing with a vertical descent. The astronauts remarked that "The LM footpads are only depressed in the surface about 1 or 2 inches." This is confirmed by the depths of penetration visible in photographs.

The descent ladder on the LM is attached to the fixed portion of the landing gear, and the footpad, by compressing the shock absorber, can move up to 32 inches with respect to the ladder. This movement decreases the distance from the bottom step of the ladder to the footpad. With no compression of the shock absorber, the distance is close to 3 feet As evidenced by both the astronaut remarks and returned photographs, hardly any stroking of either the primary or the secondary shock-absorbing struts occurred.

It is estimated that the stroking of the primary shock absorbers was about 0 to 1 inch. It is apparent, therefore, that the astronauts achieved almost a static landing on the lunar surface as far as the landing gear is concerned.

APOLLO 12

Descent and Touchdown

Descent. The descent profiles of Apollo 11 and 12 lunar modules differed considerably in the last 200 feet. Apollo 11 descended at about 2 feet per second to a height (as measured from the surface to a level plane through the footpads) of about 5 to 8 feet, and then paused at this elevation for 13 seconds before descending the final 7 feet to the surface in 3 seconds. By comparison the lunar module of Apollo 12 made the last portion of the descent at about 1.5 feet per second 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 feet. 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.

The data indicate a considerable difference between the Apollo 12 spatial descent people and that of the Apollo 11 descent. The lateral velocity of the Apollo 11 vehicle was relatively high, at about 3 feet per second, for most of the final 20 or 30 seconds of flight. The Apollo 12 spacecraft approached at a lateral rate of about 1.5 feet per second and slowed down to just over 1 foot per second 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 posed a potential hazard to future lunar landings, and it was 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 percent than that of Apollo 11. The impairment of visibility may have been 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 was 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 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.

Table 1. Comparison of Altitudes at Which Similar Events Occur on Descent.

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

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. The gross mechanical properties of the lunar surface material turned out to be 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. The evidence available of lunar surface material property variation is still not sufficient at present to enable a decisive conclusion to be reached as to its effect on rocket erosion.

Landing

Following engine shut-down when the footpads were about 5 feet 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 1 inch. The -Y footpad penetrated deeper, about 4 inches, and disturbed the surface material to a greater extent than the others.

As in the Apollo 11 photographs, the surface under the descent engine and adjacent to the footpads 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 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 to 40 feet above the surface at a position where the path is just visible.

The Apollo 13 mission did not land on the lunar surface.

APOLLO 14

Descent and Landing

Blowing Dust. The astronauts commented that blowing dust was first observed at an altitude of approximately 100 feet and that the quantity of dust from that altitude down to the surface seemed less than had been encountered during the Apollo 11 and 12 landings. The crew estimated the thickness of blowing dust to be less than one-half foot; rocks were readily visible through it. The sun angle at landing was higher for the Apollo 14 mission than it had been for the Apollo 12 landing. The appearance of the blowing lunar-surface material in motion pictures taken during the Apollo 14 descent seems qualitatively similar to that observed during the Apollo 11 landing. Dust was first observed at altitudes of 73, 100, and 100 feet for the Apollo 11, 12, and 14 landings, respectively. Because of the effect of sun angle and spacecraft orientation, however, the appearance of the dust in the motion pictures may not be a reliable indication of the quantity of material removed from the surface.

Surface Erosion. The astronauts reported that the lunar surface gave evidence of the greatest erosion in an area approximately 3 feet southeast of the region below the engine nozzle, where as much as 4 inches of surface material may have been removed during the landing. Except for a disturbed area in the left middle distance, the surface gives the appearance of having been swept by engine gases in the same way as on previous missions. The disturbed area may have developed as a consequence of grazing contact of the +Y footpad contact probe during the landing.

In the Apollo 14 descent motion pictures, it is evident that the lunar surface remains indistinct for a number of seconds after descent-engine shutdown. This event was probably caused by venting from the soil of the exhaust gas stored in the voids of the lunar material during the final stages of descent. The outflowing gas carried with it fine soil particles that obscure the surface.

Implications of Blowing Dust. The lunar soil removed by the engine exhaust gas is ejected radially from the surface below the spacecraft at predominantly low angles to the horizontal. There is thus, during the descent, a region from which soil is being removed, and an adjacent region, kilometers in lateral extent, on which the ejected particles descend. Since the spacecraft traverses laterally over the surface at a decreasing altitude, erosion in some regions will be followed by deposition of particles removed at later times from other areas.

The entire region in the vicinity of the landed spacecraft to a radius of about 900 feet is particularly subject to this process, which may have some implications in the analyses of the soil and rock samples collected. The special environmental sample obtained from material in the bottom of the trench dug at station G may be used as an example. It is likely that this soil sample included granular fragments both from below the surface and at the surface, since material fell into the trench as it was being excavated.

During descent to its landed position, the lunar module followed a track approximately W22^{o}N, going slightly south of the center of North Crater. The space craft was about 200 feet south of station G at its point of closest approach, and at this point its altitude above the lunar surface was 180 feet. (Station G is slightly south of due east of the landing site at a distance of about 750 feet.) In the descent movie, the first signs of blowing dust are visible as the spacecraft passed over North Crater. Consequently, a small amount of erosion took place at station G as the spacecraft passed by during descent. This erosion is probably not significant to the analysis of the special environmental sample. However, the amount of material removed from the surface increases greatly as the spacecraft descents, and major quantities are eroded from the landing site.

The concentration of particles arriving at station G and originating from the landing site can be estimated by comparison with the observations of the Apollo 12 mission. The Apollo 12 lunar module landed 510 feet from the Surveyor 3 spacecraft, which at the time had been on the lunar surface 31 months. Detailed study of the Surveyor-3 camera revealed a distinct shadow pattern on the paint, and this pattern was shown[11] to arise from a lunar soil sand blasting. It was demonstrated, moreover, that the sand-blasting particles came from the Apollo 12 landing site rather than from a sequence of points along its landing track. The particles must have had a velocity greater than about 13 feet per second with a shallow angle trajectory to have reached the Surveyor spacecraft and must have arrived at a fairly high concentration to have achieved the sharpness of shadow effect observed. The abrasion appears to be uniform, and there is no indication of individual impacts. Therefore, the surface or surface coating has been struck by so many particles that their impact areas overlap. It will be assumed that the majority of particles reaching Surveyor were of micrometer size or larger and that the average diameter of each impact might be of the order of 10 μm. If it is further assumed that the area of impacts just saturates the surface (conservative), it appears that each square centimeter of the abraded area was subjected to impact by about 10^6 particles. The writer also examined the Surveyor 3 surface sampler (also exposed to blowing dust) in detail at about 100 magnification, at which he should certainly have been able to see any impact marks in the size range of order 100 μm, but there were none. Therefore, it can be tentatively concluded that each square centimeter of the Surveyor camera saw at least 10^4 particle impacts from the material eroded by the descent engine.

As a check, it is found that these numbers correspond to removal of the lunar soil to a depth of 7 to 10 inches over a diameter of 15 feet from the lunar surface below the descent engine nozzle. This is compatible with astronaut observations.

If it is assumed that the Apollo 12 and Apollo 14 vehicles eroded identical quantities of lunar soil in the final stages of touchdown and that the emitted particle cloud expands spherically, the density of the particle cloud at station G would be $(155/230)^3 = 0.3$ of that at the Surveyor 3 location. Consequently, it would appear that each square centimeter of surface at right angles to the unobstructed line joining station G to the landing site would receive of the order of 10^3 impacts of particles, a few microns or more in diameter, ejected from the landing site. To reach station G, the particle velocities would need to be of the order of 300 feet per second or greater, depending on their ejection angle.

Footpad-Surface Interaction. The response of the soil to the landing (which occurred with little or no shock-absorber stroking) and the appearance of the soil in the footpad photographs suggest that the mechanical properties are similar to the mechanical properties of the lunar material on which the Apollo 11 and 12 lunar modules landed. The penetration of the +Z and +Y footpads caused the lunar module to tilt 1 to 1.5 degrees in the westerly and northerly directions. Consequently, at the landing site, the strike of the lunar surface slope is approximately W16°N, and the dip is approximately 5.5 degrees in the direction N16°E.

APOLLO 15

Soil Behavior During LM Descent and Landing

The Apollo 15 descent was much steeper and considerably slower than those of previous Apollo landings. The final 100 feet of descent occurred essentially vertically in a period of approximately 60 seconds. In earlier landings only the last 9 to 18 feet of descent were more or less vertical and occupied about half the time required for the Apollo 15 LM to descend through the same distance. The crew commented that they observed the first lunar-surface dust movement resulting from their landing at a height of approximately 140 feet and noted that the last 54 feet of descent was accomplished under conditions of no surface visibility as a result of the quantity of lunar soil being eroded by the descent engine. These were, therefore, the poorest visibility conditions during any Apollo landing. Previously, blowing dust had caused major difficulties only in the Apollo 12 descent and then only in the final one and one-half feet. The dust problem may be related to the nature of the descent path and vertical velocity as well as to the local soil and the sun-angle conditions.

Once again, from the photographs of the landing gear taken on the lunar surface, no stroking of the shock absorbers is evident, indicating only small dynamic impact forces during landing. Only nominal penetration of the footpads into the lunar surface to a depth of a couple of inches occurred. However, in the landed position, the LM tilted up to the north and west approximately 8 degrees because of the lunar-surface topography. The +Z and +Y footpads appeared to have landed on a slight rise, whereas the -Z footpad rests in a shallow crater 15 to 18 feet in diameter. The -Y footpad is also in a slight depression. The LM is oriented with the +Z axis (the leg with the ladder) pointing due west. In the landing, principally as a consequence of the topographic relief, the descent-engine bell contacted the surface, crushing the bell slightly. The Apollo 15 mission is the first on which this has occurred and it may have resulted, in part, from the fact that the Apollo 15 LM engine bell is larger than those used in earlier missions. No photographs showed any lateral translation of the footpads during the final stages of descent. Because the underside of the LM so closely approached the lunar surface, the surface area below the spacecraft was largely in shadow, and signs of the erosion that took place in descent are not evident. In addition, on this mission, the photographs of the area around the landed LM were not taken soon enough after landing to show the surface undisturbed by the astronauts' surface operations.

APOLLO 16

Soil Observations During LM Descent and Landing

During the final stages of descent, the LM crewmen reported the first signs of blowing dust between altitudes of 78 and 48 feet above the lunar surface.

However, the crewmen also indicated that the surface was clearly distinguishable all the way to touchdown and that no visibility difficulties were caused by the blowing dust. Examination of the descent movie confirms these comments. Indeed, blowing dust during the Apollo 16 landing seems to have caused the least visibility problem of all the Apollo LM landings to date.

As noted previously, the appearance of the moving dust sheet, caused by the interaction of the descent engine with the granular lunar surface, is a complex phenomenon. It depends on the small-scale nature of the surface, on the engine thrust, probably on the rate and angle of descent, on the viewer's location, and on the sun angle. Not enough is yet known about the detailed structure of the lunar-surface material to determine if it varied significantly from site-to-site, so the effect of this factor cannot be assessed. Because the landing was delayed beyond the planned time, the sun elevation was higher than on previous missions, and this may have contributed substantially to the improved viewing conditions.

The vertical descent rate was somewhat higher than that of previous missions. From an altitude of 195 feet to contact with the lunar surface, the elapsed time was less than 50 seconds. The average descent velocity from an altitude of 195 to 79 feet was approximately 5.2 feet per second; from 79 feet to contact, the average velocity was approximately 3 feet per second. For the final 90 feet of descent, this vertical velocity component was twice as great as that of the Apollo 15 landing, during which the last 55 feet of descent were accomplished with a surface visibility of zero.

The actual landing was relatively soft with little or no stroking of the shock absorbers. Penetration of the footpads into the lunar surface was minimal, with the greatest penetration of 3 to 4 inches indicated for the -Y footpad on which the cosmic ray detector was mounted. The bottom panel of the detector was the only panel to which a small quantity of lunar dust adhered. The dust, presumably deposited on the panel during landing, is apparent to a height of approximately 8 to 10 inches above the base of the pad or 4 to 6 inches above the lunar surface in the postlanding position of the footpad.

In contrast to the Apollo 15 landing, the descent engine bell of the Apollo 16 LM did not appear to contact the lunar surface; the postlanding clearance was about 58 inches.

APOLLO 17

Soil Observations During Lunar Module Descent and Landing

Both the postmission descent trajectory data and the crew comments indicate that the Apollo 17 descent was fairly rapid with vertical velocities of approximately 3 to 4-1/2 feet per second at altitudes of 183 to 214 feet above the lunar surface, slowing to somewhat less than 3 feet per second at an altitude of approximately 50 to 70 feet. The descent was accompanied by a fairly constant forward velocity of approximately 0.7 meter per second in the final 60 feet of descent. Thus, the lunar module (LM) came in on an oblique trajectory similar to that of Apollo 14. Previous analyses and mission results have shown that this kind of trajectory causes least disturbance of the lunar surface material during landing. In contrast, vertical descents, such as that of the Apollo 15 LM, generate substantial amounts of erosion. Blowing dust was first observed at a height of approximately 60 feet above the lunar surface but caused no visibility difficulties during the final descent; in fact, the surface remained clearly visible all the way to contact.

The descent engine was shut down approximately 1 second after contact was indicated, and the LM dropped to the lunar surface while maintaining some forward velocity. The crew noted that the rear (-Z) footpad probably hit the lunar surface first and that the primary shock absorber may have stroked slightly. Photographs showed some crumpling of the Mylar insulation on the lower portion of the leg, indicating a possible stroking of 1 or 2 centimeters. This crumpling did not happen on any of the previous missions. From the photographs, no crushing of or damage to the footpad can be observed.

As in the other landings, the descent engine exhaust swept the lunar surface in the vicinity of the landing site. Compared to adjacent areas, there were relatively fewer small rock fragments and soil clumps beneath the LM, although rocks 4 inches in diameter and larger remained. The crew observed that there were clear indications of the interaction of the descent propulsion system exhaust gas with the lunar surface to a distance of approximately 150 feet from the LM.

From the crew's comments during sampling, the lack of blowing dust during the final stages of the descent does not appear to be caused by soil properties different from those experienced in prior landings. The grain size distribution, cohesion, and density of the soil around the LM were similar to those previously established for lunar soil. This similarity tends to confirm previous conclusions that the amount of blowing dust during a landing is directly related to the descent trajectory and descent rate.

Other Investigations

As part of the Soil Mechanics Experiment Team for Apollo, the writer took part in a number of other activities including crew training, debriefing, and examination of returned lunar samples. Some investigations related to these activities have been reported.[12, 13, 14]

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