Reports

Lunar Surface Strength: Implications of Luna 9 Landing

Abstract. *The ability of the lunar surface to support statically the Luna 9 capsule indicates that the surface can bear at least* 5×10^3 *dyne per square centimeter* (10^{-1} *lb/in.*^{2}). *Analysis of the landing dynamics, using available data, gives a lower bound of about 1 to* 2×10^5 *dyne/cm*^{2}, *but this estimate may not be conservative because of uncertainties regarding the shock-absorbing system used and the direction of the velocity vector at impact.*

According to published information, the Luna 9 landing capsule had a mass of 100 kg (*1*), was approximately spherical in its landing configuration (*2, 3*), and was "about two feet tall" (60 cm) (*4*). One report (*3, 5*) gave the landing speed as "several" meters per second, another (*6*) stated that the capsule was ejected, less than 1 second before impact, from a vehicle moving at less than 16 km/hr (10 mile/hr). These data permit calculation of lower bounds for lunar surface strength at the point of impact; we consider three separate treatments, one static and two dynamic.

For a static solution, assume that the sphere sank a distance (s) equal to its radius (r), here taken as 30 cm. For a mass (m) of 100 kg, the statically supported mass/area ($m/\pi r^2$) is then 30 g/cm^2 (mass bearing capacity, *7*); under lunar gravity, the corresponding bearing capacity is 5×10^3 dyne/cm^2 (0.07 lb/in^2).

The first dynamic solution is based on energy balance, and assumes that the surface deforms by compression under a local bearing load. The following simple analysis should give an adequate approximation. The kinetic energy (E) of the sphere reaching the surface with velocity v is $\frac{1}{2} mv^2$. This energy goes into deformational energy of the soil (E_d) and kinetic energy of the soil (E_k), so that $E = E_d + E_k$. The deformational energy E_d may be taken as the product of the bearing force F_d and the distance the capsule moves through the soil, $F_d s$; F_d is taken as $\sigma(\pi r^2)$, σ being the bearing capacity.

To obtain the kinetic energy transferred to the soil, a volume of soil $\pi r^2 s$ is assumed to be accelerated to the average velocity ($v/2$) of the sphere during the deceleration; thus

$$E_k = (\tfrac{1}{2})\rho(\pi r^2 s)\,(v/2)^2 \qquad (1)$$

where ρ is the soil density. By combination of the above expressions

$$(\tfrac{1}{2})mv^2 = \sigma(\pi r^2)s + (\tfrac{1}{2})\rho(\pi r^2 s)\,(v/2)^2 \qquad (2)$$

or

$$\sigma = (mv^2/2\pi r^2 s) - (\rho v^2/8) \qquad (3)$$

A capsule released vertically downward at 450 cm/sec (10 mile/hr), and falling 1 second under lunar gravity, has a velocity of 610 cm/sec (20 ft/sec). The published information (*6*) indicates that the impact velocity of Luna 9 was lower, but "several" meters per second (*3, 5*) suggests at least 300 cm/sec.

If the soil density is negligible, for $v = 300$ cm/sec Eq. 3 gives the bearing capacity as 5×10^4 dyne/cm^2; for $v = 610$ cm/sec it gives 2×10^5 dyne/cm^2; the corresponding mass bearing capacities are 300 and 1000 g/cm^2, respectively.

Radar data (*8*) indicate that the soil density deeper than a few tens of centimeters is about 1.5 g/cm^3. When this value is used in Eq. 3, the bearing capacity, for $v = 300$ cm/sec, is 4×10^4 dyne/cm^2; and for $v = 610$ cm/sec it is 1.5×10^5 dyne/cm^2; corresponding mass bearing capacities are 200 and 900 g/cm^2, respectively. On the basis of the above assumptions, the lower bound for lunar bearing capacity is thus 4×10^4 to 2×10^5 dyne/cm^2.

As an alternative dynamic approach, equations of motion previously established (*9*) to treat low-velocity penetration into an incompressible medium were used. In the motion, the kinetic energy of the projectile is expended in shearing the medium and accelerating the material from the path of movement; a rational, quasi-static deformation mechanism in the medium is employed.

For simplicity in calculation, the spacecraft was represented by a right circular cone (tip angle, 90°; base diameter, 60 cm; height, 30 cm) attached at its base to a right circular cylinder (diameter, 60 cm; length, 30 cm). The combination was given the mass (100 kg) of Luna 9. Impact was considered to occur with the apex of the cone down and with the axis of the body normal to the surface, which was perpendicular to the direction of the local gravity field. A computer program, previously written to deal with this situation, was used; the program was written in terms of a cohesive, incompressible material. For the lunar case, three soils, behaving thus and having the properties shown in Table 1, were treated in the analysis; the values of cohesion were selected to give the surface bearing capacities shown (the bearing capacity at the surface of a cohesive soil is approximately five times the cohesive shearing strength of the soil).

The maximum depths of penetration of the spacecraft into the three soils were calculated at two impact velocities: 305 and 610 cm/sec (Table 2). Because the presumably spherical shape presented by Luna 9 to the lunar surface was represented by a cone in the calculations, these depths of penetration are too high, but it is felt they give

Table 1. Properties of three (assumed) incompressible soils.

Soil No.	Density (g/cm^2)	Cohesion (dyne/cm^2)	Bearing capacity, surface (dyne/cm^2)
1	0.77	1.5×10^4	8×10^4
2	1.55	1.5×10^5	8×10^5
3	1.55	1.5×10^6	8×10^6

Table 2. Calculated maximum depths of penetration by Luna 9 into three assumed soils.

Soil No.	Penetration (cm) from initial velocity	
	305 cm/sec	610 cm/sec
1	37	52
2	18	24
3	9	12

a good indication of the order of the penetration and its relative magnitudes in the different soils.

It would seem, therefore, from the penetration analysis, that the successful landing and operation of Luna 9 (penetration less than 30 cm) occurred on a surface that was harder than that represented by an incompressible cohesive soil having a cohesive shearing strength of, say, 5×10^4 dyne/cm^2, corresponding to a bearing capacity of 2 to 3×10^5 dyne/cm^2 and a mass bearing capacity of about 1000 g/cm^2. This value is consistent with that given by the energy approach. (The pressure exerted by an astronaut standing on the lunar surface ranges from 3 to 7×10^4 dyne/cm^2; supported mass, 200 to 500 g/cm^2.)

It must be noted, however, that a shock-absorbing system was used to cushion the capsule impact (*3, 6*); accordingly, some of the energy did not go into the soil. Moreover, the velocity vector at impact was not necessarily vertical. For both these reasons the dynamic treatments used are not conservative. Thus the bearing capacity may be less than the 1 to 2×10^5 dyne/cm^2 given by the dynamic analyses, and only the value of 5×10^3 dyne/cm^2, derived from static considerations, seems a truly safe lower bound; the latter value (corresponding to 30 g/cm^2 mass bearing capacity) is no higher than one derived from Ranger-7 data (*10*).

The bearing capacities of hard terrestrial rocks are of the order of 10^9 dyne/cm^2. Available information on the Luna 9 landing thus provides no basis for statements that the lunar surface is hard rock; on the contrary, the landing statics and dynamics are not inconsistent with the properties expected under lunar conditions for highly porous fairy-castle structures (*11*).

We may point out that more information on the mechanical properties of lunar-surface material will be obtained if an upper bound can be established; this would require observation of surface displacement or yielding under the application of a known force under known conditions.

This report should not be taken to advocate the view that the lunar surface consists of unsintered fine particles having low cohesion; more probably the particles show high cohesion (*11*) and need not be fine (*12*). It is not evident, however, that the successful landing of Luna 9 clarifies these questions.

L. D. JAFFE
R. F. SCOTT

Jet Propulsion Laboratory and Division of Engineering and Applied Sciences, California Institute of Technology, Pasadena

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Atmospheric Gases and Particulates in Panama

Abstract. *The concentrations of trace gases in tropical air from samples taken on the Isthmus of Panama are compared with those reported by others. The role of a tropical land mass as a sink or source of atmospheric components is discussed.*

The National Center for Atmospheric Research and the Tropic Test Center of the U.S. Army Test and Evaluation Command have undertaken a cooperative study of the atmosphere of the Isthmus of Panama to characterize the sinks and sources for trace atmospheric components in the tropics. The results obtained so far are sufficiently unexpected that we are reporting our findings. While the total number of measurements is limited, they are sufficiently spread in time, and the range is sufficiently small, that it seems unlikely that further data would qualitatively change our conclusions.

We have taken samples in Panama during three periods, each about 2 weeks in length. One period was during the rainy season, in November 1965, and the other two were during the dry season, in February 1965 and the same month in 1966.

The orientation of the Canal Zone and the Isthmus of Panama is shown in Fig. 1. The predominant wind direction across the Isthmus is northerly. This wind stems from the Bermuda high, and its direction shifts between the dry and rainy seasons, reflecting the shift of the Bermuda high over the Caribbean.

There were three major sampling sites. The first was at Fort Sherman, on the Caribbean (northern) side of the Isthmus. All samples from this area were collected a short distance from the shore and thus represent tropical maritime air typical of the Caribbean. The second sampling site was a meteorological tower in Albrook Forest near the Pacific (Bay of Panama) side of the Isthmus, a semideciduous tropical rain forest. The tower is about 50 m high, permitting sampling both above and below the forest canopy. The third sampling site was on the north side of the Pearl Islands Archipelago in the Bay of Panama. Typical air trajectories to this site have traversed the Isthmus and then a short distance over the ocean surface. They do not cross the Canal Zone, and thus are not influenced by the human activity of the Zone.

A few samples were collected at a subsidiary site on Madden Ridge Road. This site is on the Continental Divide, in the path of Caribbean air which has traversed 50 km of virgin forest.

Although the samples collected thus far are considered preliminary, some reliable estimates of concentrations of gases and particles in the atmosphere have been obtained. Junge (*1*) summarizes previous measurements and gives a range of probable concentrations in the atmosphere. These concentrations are admittedly uncertain owing to the paucity of previous measurements, and it is interesting to compare Junge's data (converted approximately into consistent units) with our estimates for various gases and particulates.

Junge cites the few formaldehyde measurements which have been made, and gives a probable ground-level concentration range from 0 to 10 ppb (parts per 10^9). He points out that these