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Basic and Mechanical Properties of the Lunar Soil Estimated From Surveyor Touchdown Data

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Preface

The work described in this report was performed by the Engineering Mechanics Division of the Jet Propulsion Laboratory.

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Abstract

Presented are the results of a study that was performed to estimate the following basic and mechanical properties of the lunar soil:

(1) Bearing strength.

(2) Effective friction coefficient.

(3) Bulk density.

(4) Internal friction angle.

(5) Relative density.

Surveyor landing telemetry data served as input; the method used was the analytical simulation of *Surveyor* landings with two analytical soil models.

Basic and Mechanical Properties of the Lunar Surface Soil Estimated From *Surveyor* Touchdown Data

I. Introduction

One of the primary objectives of the *Surveyor* missions was to obtain estimates on the basic and mechanical properties of the lunar surface soil. A "touchdown instrumentation study" was specifically initiated to accomplish this objective, and the result of the study was a proposal for a flight instrumentation package. However, because of budgetary and schedule problems, the flight instrumentation was not developed.

Therefore, a study was performed to determine a method of obtaining as much as possible of the desired information with existing engineering instrumentation. The study was mainly concerned with the information obtained from strain gage bridges mounted on the *Surveyor* landing gear (Fig. 1). The strain gages monitored axial loadings in each of the three landing-leg shock absorbers; strain gage output was received in the form of continuous frequency modulated analog data.

The strain gage data reflected the ground resistance acting on each footpad during touchdown; this resistance varied considerably during touchdown, both in magnitude and direction, as a result of one or more of the following factors:

(1) Change in leg geometry during touchdown.

(2) Sidewise motion of footpad during touchdown.

(3) Sliding of spacecraft caused by ground slope.

A single strain gage reading does not provide sufficient data for determining both magnitude and direction; therefore, the ground reaction force (an important factor of surface soil behavior) could not be determined. However, an analytical landing simulation program, which had been developed and successfully used for preflight stability and landing load studies, was used to obtain data on the ground reaction force.

Simulation of the entire landing was based on the following information:

(1) Landing velocity (determined from approach radar data).

(2) Position of spacecraft relative to the ground (derived from leg impact timing as indicated by strain gage data).

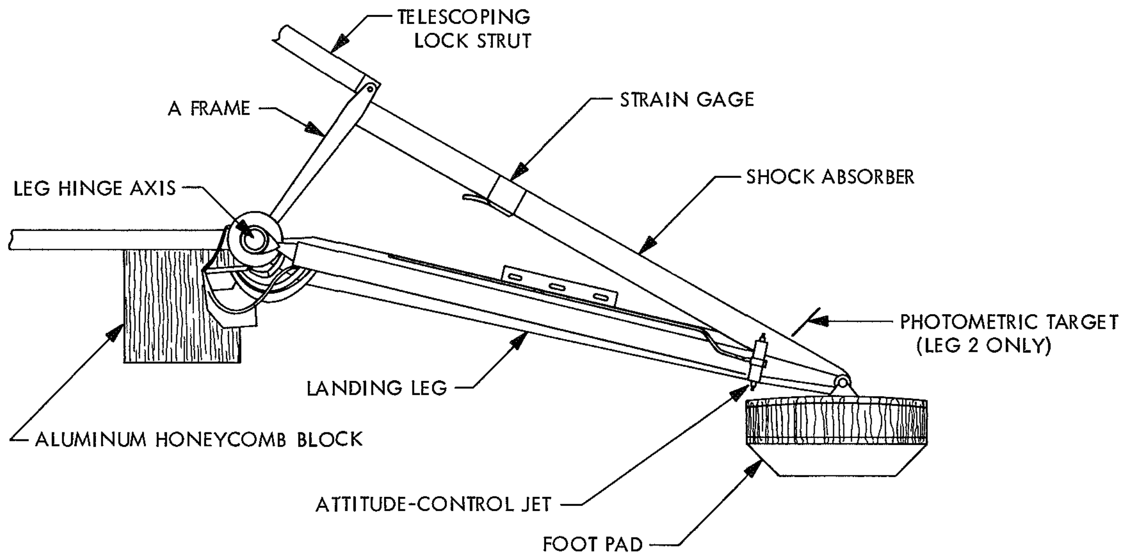

Fig. 1. ***Surveyor*** **landing gear in extended position**

A comparison of the strain gage histories of the simulation with those of the lunar landing was used to validate the simulation. After a representative simulation was obtained, all landing forces including the desired horizontal and vertical footpad–ground forces were available for the entire landing process. However, because footpad photographs indicated that the landing surface was not rigid, the approach given above was modified to include an analytical soft-soil representation. The amount of footpad penetration, as estimated from the photographs, served as an additional indicator for the quality of the landing simulations.

II. Coefficient Soil Model and Bearing Strength

Since practically no soil mechanics work applicable to low-velocity impacts was available, and since the program had to be ready for the first *Surveyor* mission, a simple coefficient model was devised to represent the soil. This model is composed of two equations, one each for the vertical and horizontal components of the soil resistance.

The vertical soil-force component F_v consists of a constant term, a term linearly depending on the penetration depth x, and a third term proportional to the square of the penetration velocity. The horizontal soil force F_h is assumed to be made up of a conventional surface friction term, a term varying linearly with depth, and a "plowing" term proportional to the product of penetration depth and the square of the sliding velocity $\dot{y}$:

$$F_v = C_1 + C_2 x + C_3 \dot{x}^2$$

$$F_h = C_4 x \dot{y}^2 + C_5 F_v + C_6 x$$

Each term carries an arbitrary coefficient, and it was hoped that by varying their values from simulation to simulation, one "soil" would be found that would respond to a simulated *Surveyor I* landing with strain gage histories and footpad penetrations matching those of the actual landing and, hence, afford estimates of the bearing strength, its linear change with depth, and the frictional behavior of the lunar surface material.

After the landing of *Surveyor I* (Ref. 1), a study was conducted with the coefficient soil model. The results are contained in Ref. 2; however, the estimated *Surveyor I* footpad penetrations have since been revised. The revised penetration data indicate that the lunar soil (most likely to exist at the *Surveyor I* landing site) has a bearing strength between 0 and 2 psi in its very top layer and a strength of 4 to 6 psi at a depth of 1 in. This revised estimate of the lunar soil is slightly firmer than that specified in Ref. 2. Since bearing strength is not a basic soil property and may be quite different for other loading conditions, the estimates apply only to the *Surveyor* landing parameters; i.e., a 45-deg beveled footpad with an 8-in. baseplate radius (see Fig. 1), impacting with a velocity of approximately 12 to 13 ft/s.

The spring and damping characteristics of the shock absorber are also important for the encountered loading condition; of course, the determined bearing strength values are only as good as the ability of the coefficient soil model to represent real soil behavior.

III. Frictional Behavior of the Surface

Estimates for the three coefficients in the horizontal ground force equation proved to be more difficult to obtain than expected, primarily because neither the penetration depth nor the strain gage load histories seemed to be very sensitive to variations in the horizontal force representation. Therefore, the equation was simplified to the form of a conventional surface friction force, i.e., an "effective friction coefficient" C_5 to be multiplied by the instantaneous ground pressure; C_5 was the only variable that had to be determined (C_4 and C_6 were assumed to be zero). Even this one variable could not be ascertained very closely; however, values between 0.5 and 0.8 appeared to be most consistent with the received landing telemetry from *Surveyor I*.

Surveyors III, V, VI, and *VII* also landed successfully but, because of a change in the carrier frequency of the strain gage telemetry channels, the data received during their landings were inferior in quality to the *Surveyor I* data. In addition, *Surveyor III* did not cut its engines as planned before touchdown; therefore, its landing was unsuitable for this type of soil analysis. For *Surveyors V, VI,* and *VII,* landing simulations have been performed that show no basic difference from the findings of *Surveyor I. Surveyor V,* however, seems to have encountered a slightly softer soil, but this may be explained by the fact that its landing took place on a surface with a slope of approximately 20 deg (Ref. 3). Because of the sloping landing area, the footpads of *Surveyor V* slid 2–3 ft downhill before coming to rest (Fig. 2). Although this fact renders the *Surveyor V* landing less suitable for the soil evaluation described above, it does afford an opportunity for the estimation of the horizontal force that acted between footpad and ground during the slide.

If a simple friction force with a constant friction coefficient is assumed, the problem is basically that of a body sliding on an inclined plane. Since in this problem the weight of the body is immaterial, the fact that the ground pressure underwent large fluctuations during the slide-out period does not invalidate the approach.

The slide-out distance can be closely estimated from Fig. 2, and there are indications in the digital telemetry of *Surveyor V* that allow a close estimate of the time from first contact to final settling. However, knowledge of these three conditions—impact velocity, slide-out distance, and slide-out time—makes the problem overdetermined (the slope is also known and assumed to be constant), so that three different values for the friction coefficient result, depending on which two of the three known conditions are used. Consequently, three values, 0.67, 0.74, and 0.80, have been obtained for the effective coefficient of sliding friction; the value of 0.67 is regarded as more reliable than the other two because it is based on slide-out distance and time, both of which are accurately known.

In addition, the landing simulation approach described above was used to determine the friction coefficient by matching the slide-out distance. A value of 0.63 was determined by this method.

In summary, then, a value between 0.6 and 0.8 was obtained for the friction coefficient with three different methods: (1) *Surveyor I* computer simulations matching strain gage data and footpad penetrations, (2) *Surveyor V* computer simulations matching strain gage data and slide-out distance, and (3) inclined plane calculations matching slide-out distance and slide-out time. However, it must be emphasized that this value does not constitute a true coefficient of friction. Simultaneously with a downhill slide, *Surveyor V* rebounded because of the spring action of the landing legs. Although it appears that the footpads did not clear the surface (see Fig. 2), there was (for approximately 0.7 s) no normal pressure acting on the footpads; consequently, their sidewise motion was restrained only by the surface material that had to be pushed out of the way by the beveled sides of the footpads. During the remaining time, there was friction resulting from pressure on the faceplates of the footpads; however, part of the horizontal resistance was again due to "plowing."

Therefore, the true value for the surface friction coefficient is most likely to be lower than 0.63. However, the "effective friction coefficient" is probably of more practical value than the true surface friction coefficient because, due to the low bearing resistance of the top layer of the lunar surface, a certain amount of sinkage will be encountered in all hardware–surface interactions on the moon. Hence, the horizontal resistance can always be expected to exceed the surface friction contribution to an extent that depends on the configuration of the interacting body and other conditions of the particular loading case.

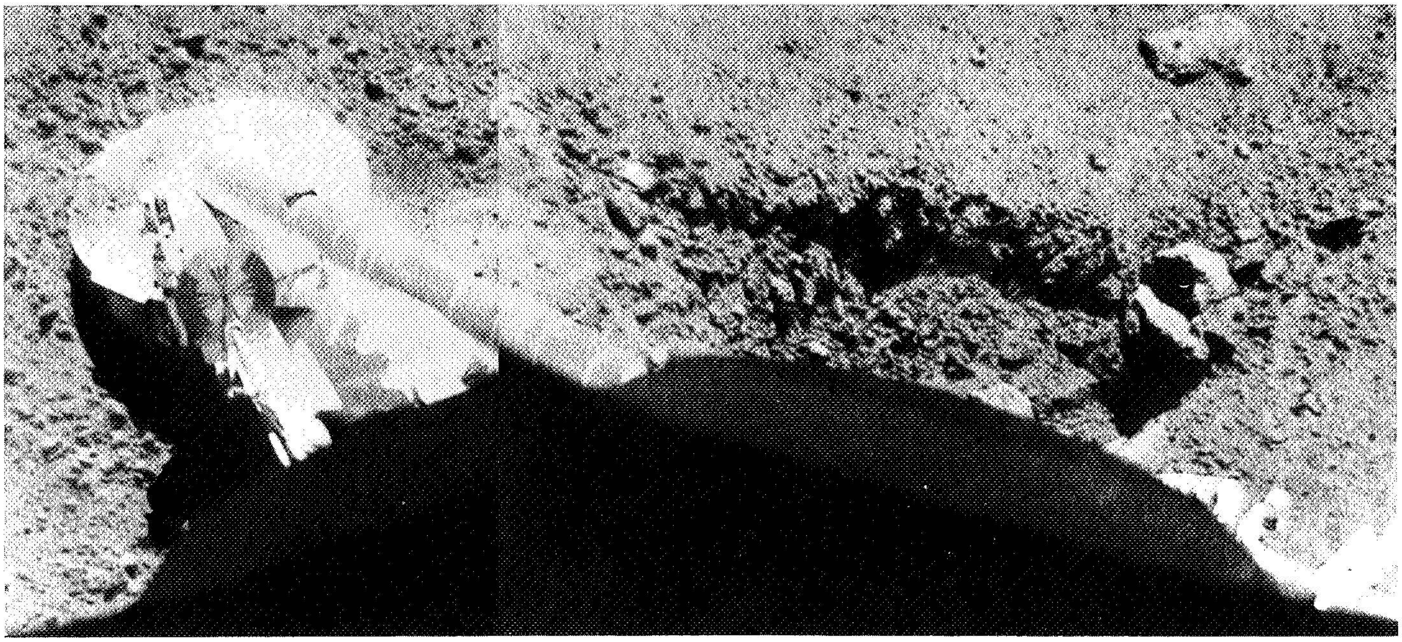

Fig. 2. Footpad 2 of *Surveyor V* after landing on a 20-deg slope

IV. Soil Model in Terms of Basic Soil Properties

Another way to represent a soil analytically is in terms of its basic physical properties. The most important basic soil characteristics of a homogeneous soil are as follows:

(1) Density.

(2) Porosity (or relative density).

(3) Cohesion.

(4) Internal friction.

(5) Grain size distribution.

Knowledge of the basic soil descriptors theoretically enables prediction of such derived soil properties as bearing strength, compressibility, and surface friction for different loading conditions. In practice, the capability of predicting soil behavior from these descriptors is not very well developed for cases involving dynamic phenomena. Nevertheless, estimates of the above characteristics for the lunar surface material are very desirable as a basis for lunar soil mechanics work. *Surveyor* was not equipped to measure any of these parameters directly; however, evaluations of footpad imprint photographs and Vernier engine firings on the lunar surface provided the following estimates of cohesion and grain size distribution (Refs. 4 and 5): cohesion, 0.007 to 0.17 N/cm^3; grain size distribution, well-graded, mean size approximately 0.06 mm, 10% or more smaller than 0.01 mm.

In addition, the alpha scattering experiment results (Refs. 5 and 6) provided a close estimate of the grain density of the lunar surface material: 3.0 ±0.05 g/cm^3 for the maria landing sites of *Surveyors V* and *VI*, and 3.2 ±0.05 g/cm^3 for the highland site of *Surveyor VII*.

An attempt was made to obtain estimates of the remaining three soil descriptors (internal friction, relative density, and bulk density) by use of the landing simulation data matching technique and a soft-soil representation expressed in terms of these unknown soil properties. Such a model, the so called interaction model, had been developed by the Bendix Aerospace Division by combining test data with an analytical approach (Ref. 7). The interaction model has the form of two force equations acting on the impacting body normal (F_{np}) and axial (F_{ap}) to its instantaneous velocity direction, as follows:

$$F_{ap} = C_{ms}\,\rho g d A_{ft} + C_D\,\rho A_{ft}\,V_{ap}^2 + 3\,\eta\rho r(d)^2\,r'(d)\left(\frac{A_{ft}}{A_{ftm}}\right)^{1.5} V_{ap}^2 \cos\theta$$

$$F_{np} = \psi F_{ap}$$

where

$$\eta = \frac{\pi}{3}\,\frac{1 + \tan\left(\frac{\phi}{2}\right)}{1 - \tan\left(\frac{\phi}{2}\right)}$$

The coefficients C_{ms} and C_d are dimensionless, and depend on internal angle of friction Φ and relative density D_r; C_d depends, in addition, on the geometric shape of the impacting body, expressed by its radius at the undisturbed surface level $r(d)$ and the contact area projections normal to the velocity direction A_{ft} and A_{ftm} ($A_{ft} = A_{ftm}$ for $\theta = 0$), and the local acceleration due to gravity g. The faceplate penetration is denoted by d, and θ is the angle between the surface normal and the velocity direction of the impacting body, the axial component of which is V_{ap}.

Finally, the dimensionless expression ψ, relating the two force components, is a function of θ and the body shape only. Hence, the three soil parameters are bulk density ρ, relative density D_r, and internal friction angle Φ. A detailed explanation and derivation of the soil force equations is presented in Ref. 8.

This interaction model was implemented by the Manned Spacecraft Center (MSC) in its lunar module (LM) landing program; rough estimates, based on experience with earth soils, were used for the three variables ρ, D_r, and Φ. The interaction model, as implemented by MSC, is hereafter referred to as the MSC soil model. The values estimated by MSC are:

(1) $\rho = 3.0$ slugs/ft^3 (1.55 g/cm^3)

(2) $D_r = 0.5$ to 0.9

(3) $\Phi = 35$ to 40 deg

It was decided that this interaction model should also be adapted to the *Surveyor* footpad geometry and landing conditions to provide a mechanism for checking the results obtained by MSC by simulating *Surveyor* landings on this "soil" and comparing the landing data (primarily strain gage histories and footpad penetrations) with those of the actual landings. In addition, it was hoped that a parametric simulation study with the interaction model would result in estimates of the three variables ρ, D_r, and Φ that could replace the values originally estimated by MSC. Such parametric studies have been performed at Bendix and JPL, in addition to a simulated *Surveyor I* landing on the MSC soil model.

The peak landing shock absorber forces of leg 1, 2, and 3, and the maximum ground penetrations of the three *Surveyor* footpads are used as indicators for comparing the simulated landings with the actual landing of *Surveyor I* (Table 1).

As Table 1 clearly shows, the MSC soil model is considerably softer than the material encountered by *Surveyor I;* this fact indicates that the results of landing simulations performed with even the strongest "Houston soil" should be considered conservative.

Before the parametric study was undertaken to estimate the values of ρ, D_r, and Φ, upper and lower bounds had to be set for these parameters. Experience with low-cohesion, fine-grain soils on earth and the value of 3.0g/cm^3 for the grain density of the lunar material (Ref. 6) were used to establish expected ranges for the three variables. The bulk density ρ and the relative density D_r are, of course, related to each other; however, knowledge of the grain density does not suffice to eliminate one of these two independent variables. Burmister's definition (Ref. 9) of relative density

$$D_r = \frac{(\rho - \rho_{\min})\,\rho_{\max}}{(\rho_{\max} - \rho_{\min})\,\rho}$$

necessitates, in addition, knowledge of $\rho_{\min}$ and $\rho_{\max}$, the densities of the soil when most loosely and most densely packed, respectively, under the laboratory conditions specified in Ref. 9. However, $\rho_{\max}$ does not indicate the highest possible packing under any conditions; consequently, the actual bulk density can exceed $\rho_{\max}$, particularly in a vacuum, in which case $D_r > 1$.

If it is assumed that the soil consists of spheres of equal size, a maximum packing of 74% is theoretically possible. This maximum packing, however, would correspond to a value of D_r that is larger than 1.0. On the other hand, $\rho_{\max}$ values of 76 to 80% of grain density have been measured for dry silica sand (Ref. 7), with $\rho_{\min}$ values between 65 and 67%. If it is assumed that the lunar material compacts quantitatively in the same manner, a relative density of $D_r = 0$ would correspond to a bulk density of $\rho = 1.96$ to 1.98, and $D_r = 1$ would correspond to $\rho = 2.28$ to 2.40 g/cm^3.

The bulk density of the lunar surface material has been estimated to be 1.5 g/cm^3 (see Section V of Ref. 6). *Luna 13* (Ref. 10) appears to have determined a density of 0.8 g/cm^3. However, simulation computer runs with $\rho = 1.5$ g/cm^3 in connection with D_r values of up to 1.1 and Φ values of up to 55 deg have indicated that the observed soil resistance cannot be obtained unless a higher value for ρ is assumed. An expected range for the angle of internal friction Φ, based on experience with earth soils, would be between 25 and 55 deg; in general, Φ increases with increasing D_r (Ref. 7).

Table 1. Simulated *Surveyor I* landings on MSC soil model

Simulation number	Bulk density ρ, g/cm^3	Relative density D_r	Internal friction angle Φ, deg	Maximum shock absorber force, lb			Maximum footpad penetration, cm		
				Leg 1	Leg 2	Leg 3	Footpad 1	Footpad 2	Footpad 3
—	—	—	—	1390 ±70[a]	1600 ±80[a]	1400 ±70[a]	—	3 ±1[a]	2.5 ±1[a]
1	1.55	0.5	35.0	1190	1200	1180	16.9	17.0	16.6
2	1.55	0.7	35.0	1260	1300	1250	12.0	12.1	11.7
3	1.55	0.9	35.0	1410	1440	1370	8.3	8.4	8.1
4	1.55	0.5	37.5	1210	1220	1200	15.7	15.9	15.5
5	1.55	0.7	37.5	1280	1320	1270	11.2	11.3	10.9
6	1.55	0.9	37.5	1420	1460	1390	7.7	7.8	7.6
7	1.55	0.5	40.0	1230	1240	1210	14.6	14.8	14.5
8	1.55	0.7	40.0	1300	1340	1290	10.4	10.5	10.2
9	1.55	0.9	40.0	1450	1490	1400	7.2	7.3	7.1

[a]Actual *Surveyor I* lunar landing data.

The density measurement determined by *Luna 13* (Ref. 10) actually resulted in two values: 0.8 and 2.1 g/cm^3. The authors of Ref. 10 considered the lower value more likely because, at that time, most astronomical, photographic, and astrophysical measurements did not suggest rocklike material on the lunar surface. However, the results of the alpha scattering experiments of *Surveyors V, VI,* and *VII,* the first of which were obtained approximately 9 mo after *Luna 13,* do indicate the presence of materials similar to earth rocks on the surface of the moon. In view of this evidence, the bulk density value $\rho = 2.1$ g/cm^3 becomes much more meaningful and seems to be in a very probable range, but the value of $\rho = 0.8$ g/cm^3 seems totally irreconcilable.

The simulated landings performed in the first part of this study clearly indicated a requirement for a surface soil of not only a high bulk density (above 2 g/cm^3), but also a high relative density (at least 0.9) to even approach a data agreement between simulation and actual landings. Consequently, a second parametric study was performed in which the following values were assumed: $\rho = 2.09$ and 2.14 g/cm^3; $D_r = 0.9$ and 1.0; $\Phi = 35$, 37.5, and 40 deg. By extrapolation from information generated in these and previous computer runs, values for ρ, D_r, and Φ can be determined that result in close agreement of simulated landing data with actual landing data of *Surveyor I* (Figs. 3 and 4). In Figs. 3 and 4, the maximum shock absorber force of leg 2 and the maximum penetration of footpad 2 were used as indicators. (Leg 2 was selected because its values were considered the most reliable.) As the extrapolation plots show, the two indicators converge toward the actual landing values approximately at the same value of the selected variable (ρ in Fig. 3, and Φ in Fig. 4), if the upper estimate of 4 cm is assumed to represent the maximum penetration of footpad 2.

Based on this assumption and subject to the other constraints inherent in the method and in the soil representation, the following best estimates are concluded to represent the lunar maria surface material to a depth of at least 4 cm:

(1) $D_r = 1.0 \pm 0.1$

(2) $\rho = 2.2 \pm 0.2$ g/cm^3

(3) $\Phi = 45 \pm 5$ deg

V. Summary and Conclusion

The purpose of the study was to estimate the following lunar soil characteristics:

(1) Bearing strength.

(2) Effective friction coefficient.

(3) Bulk density.

(4) Internal friction angle.

(5) Relative density.

Surveyor landing telemetry data served as input; the method used was the analytical simulation of *Surveyor* landings with the interaction and coefficient soil models.

The first soil model is expressed in terms of surface bearing strength, linear rise of bearing strength with depth, and effective surface friction. If it is assumed that this model represents the lunar soil, the following estimates result for the loading conditions and landing velocities of the *Surveyor* footpads:

(1) Surface bearing strength: 0–2 psi.

(2) Bearing strength at 1 in. penetration: 4–6 psi.

(3) Effective friction coefficient: 0.6–0.8.

The second soil model is expressed in terms of soil bulk density, relative density, and internal friction angle. If it is assumed that this model represents the lunar soil and that this soil can be compacted quantitatively in the same way as silica sand of approximately the same grain size range, the following estimates result, independent of loading conditions:

(1) $\rho = 2.0$ to 2.4 g/cm^3

(2) $D_r = 0.9$ to 1.1

(3) $\Phi = 40$ to 50 deg

Simulated *Surveyor* landings on the firmest soil ($\rho = 1.55$ g/cm^3, $D_r = 0.9$, and $\Phi = 40$ deg) used in MSC's preliminary soft-soil landing analysis resulted in footpad penetrations almost twice as deep as observed during the lunar landings. Consequently, the results of this analysis can be considered conservative, since the same interaction soil model was used.

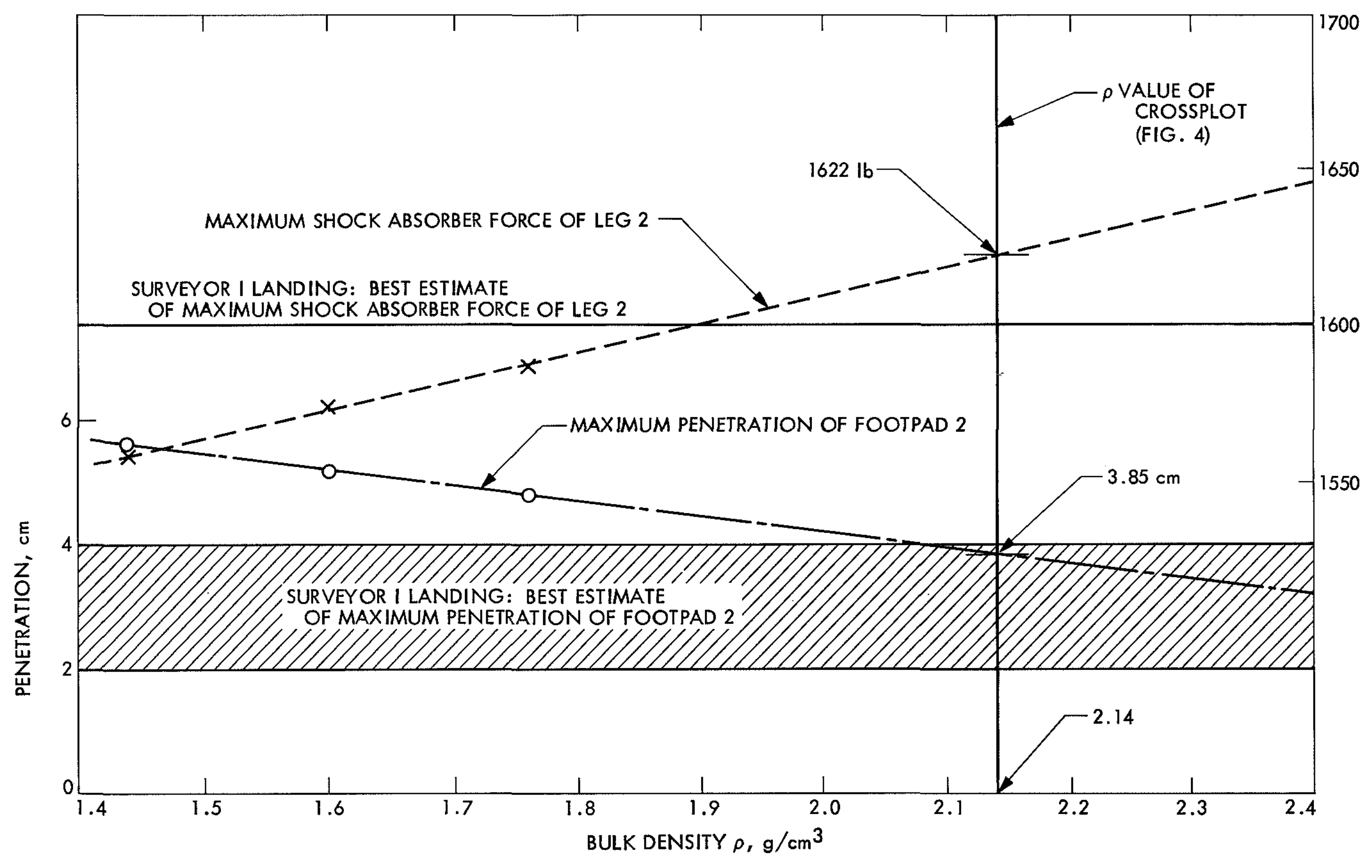

Fig. 3. Determination of ρ by extrapolation from interaction soil model data and comparison with actual *Surveyor I* landing conditions (parameters: $D_r = 1.0$, $\Phi = 45$ deg)

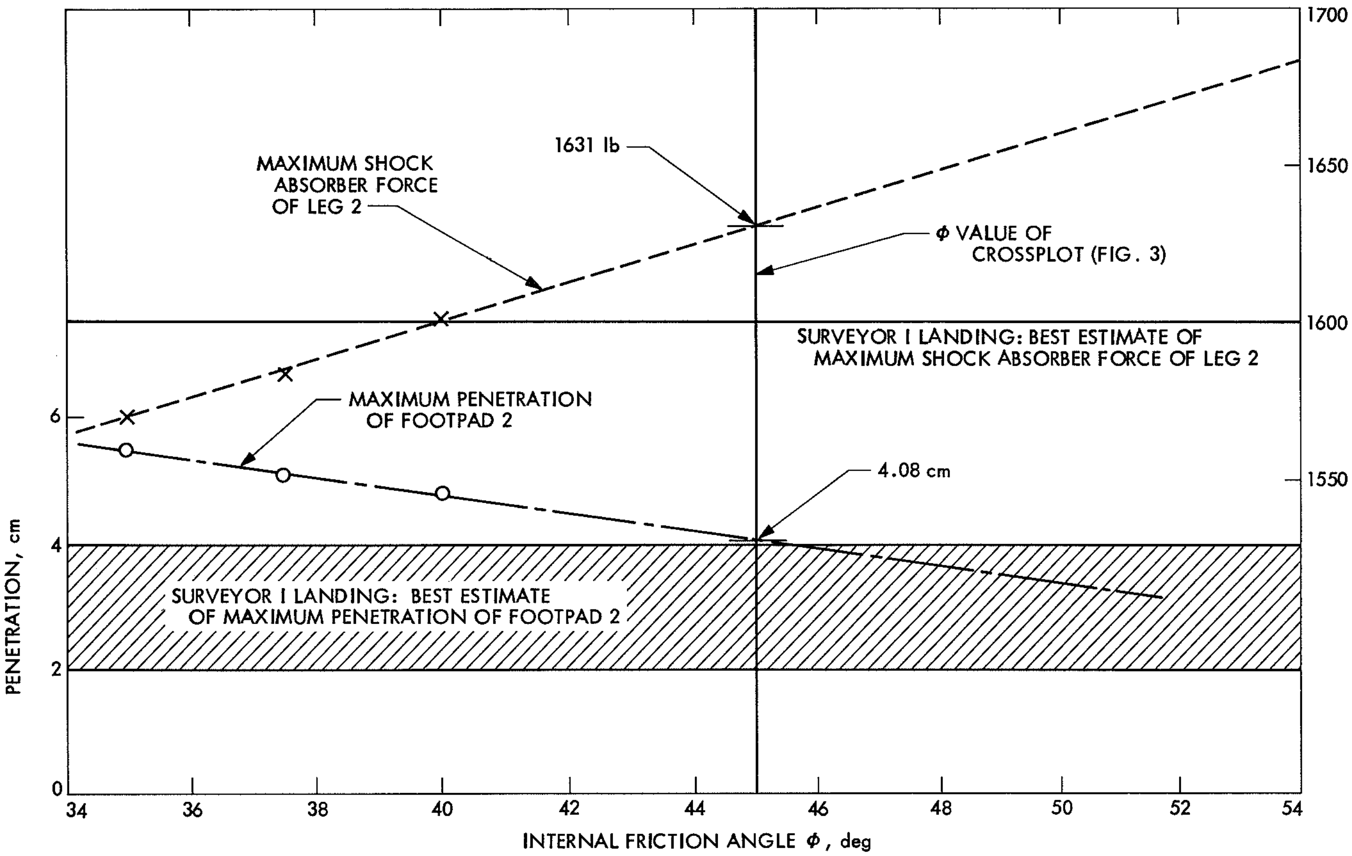

Fig. 4. Determination of Φ by extrapolation from interaction soil model data and comparison with actual *Surveyor I* landing conditions (parameters: $D_r = 1.0$, $\rho = 2.14$)

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