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Semiannual Status Report

LUNAR SOIL PROPERTIES AND SOIL MECHANICS

for the period 20 December 1971 to 20 June 1972

Principal Investigator: Prof. James K. Mitchell

June 1972

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University of California, Berkeley
Geotechnical Engineering

Semiannual Status Report

LUNAR SOIL PROPERTIES AND SOIL MECHANICS

by

James K. Mitchell
William N. Houston
H. John Hovland

Covering period from 20 December 1971 to 20 June 1972

NASA Grant NGR 05-003-406

Principal Investigator: Professor James K. Mitchell

June 1972

PREFACE

This report was prepared by the University of California, Berkeley, under NASA Grant NGR 05-003-406, Lunar Soil Properties and Soil Mechanics, for the National Aeronautics and Space Administration. Technical liaison for this work is conducted by the Assistant Administrator for University Affairs.

James K. Mitchell, Professor of Civil Engineering, serves as Principal Investigator for these studies, and William N. Houston, Assistant Professor of Civil Engineering, is coinvestigator. Dr. H. John Hovland, Assistant Research Engineer, in addition to participating in the project research, serves as project manager. Six graduate student research assistants have participated in the studies during this reporting period.

CONTENTS

LUNAR SOIL PROPERTIES AND SOIL MECHANICS

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INTRODUCTION

The research described herein represents a continuation of a program in lunar soil engineering, initiated in 1967 under contract to the Marshall Space Flight Center. In June 1970, sponsorship for continuation of this work was transferred to NASA Headquarters, Office of University Affairs. The present research grant was effective June 20, 1970, Supplement No. 1 extended the grant period until June 20, 1972, and additional funding has been provided to extend the studies an additional year.

The long-range objectives of the research described herein are to develop methods of analysis for determination of the physical properties and engineering behavior of lunar surface materials under in situ environmental conditions. Data for this purpose are obtained from on-site manned investigations, orbiting or soft-landed spacecraft, and terrestrial simulation studies. Knowledge of lunar surface material properties can be used directly in, or to establish constraints on, the development of models for several types of lunar studies and for the investigation of lunar processes. In addition, the research results will have direct engineering application should further lunar exploration and/or development be undertaken in the post-Apollo period.

FABRIC OF REAL AND SIMULATED LUNAR SOILS

by

Arshud Mahmood and James K. Mitchell

OBJECTIVES

The natural, unconsolidated surface material on earth (i.e., soil) consists mainly of various sized rock fragments composed of mineral assemblages and discrete mineral grains. Depending on the size and shape of grains, environment, and the transportation-deposition processes, many soil masses on earth acquire recognizable particle arrangements or fabrics. The mechanical behavior of terrestrial soils is significantly influenced by the fabric, at least in the case of very fine-grained soils (clays). The extent to which history and properties are reflected by fabric of soils having particle sizes in the silty fine sand range, as does lunar soil, is not known.

The present study is being carried out to identify and define any recognizable fabrics in lunar soils. A knowledge of lunar soil fabrics could lead to the identification of lunar processes that were active during the formation, transportation, and deposition of the soil deposit. When placed in the context of known regional geological features, this information can give clues to the history of the lunar regolith in different locations.

APPROACH

The following approach is being used:

A. Fabric of Simulated Lunar Soil

1. Lunar soil particle shapes, sizes and size distributions are being characterized by our own study of three small (~1 g each) samples made available

to us, (two from Apollo 14 and one from Apollo 15) and by review of published data.

2. Samples of simulant whose properties approximate those of the lunar soil particles are being prepared.

3. Recognizable grain arrangements associated with different depositional modes and densities are being determined.

4. Mechanical properties (strength, compressibility, modulus of deformation and anisotropy) associated with different fabrics will be determined. If substantial differences exist between the mechanical properties of samples having different fabrics, then it should be possible to characterize fabric in terms of these properties.

B. Fabric of Lunar Soil

The lunar soil samples made available to us will be used to study fabric types that can be developed using disturbed samples. Maximum and minimum void ratios measured for these three lunar soil samples will be used as a basis for determination of the relative densities of returned lunar core samples. A study of these small samples will help correlate the fabric of simulant to that of in-situ lunar soil.

A characterization of the "undisturbed" lunar soil fabrics can probably be made by examining the lunar drive tube samples.

STATUS

A preliminary characterization of lunar soil particle properties based on review of published literature was presented in the last report. It is now generally accepted that most lunar soil particles fall within five major particle types: agglutinates, basalt fragments, mineral fragments, micro-breccias and glasses (LSPET, 1972).

Samples of lunar soil simulant were studied for evidence of recognizable grain arrangements. It was established that soils composed of large numbers of elongate and irregular particles of silty fine sand size (such as our simulant and the actual lunar soil) are conducive to formation of different fabrics and preferred orientations of particles. It has also been possible to characterize particle arrangements numerically, thus providing a basis for quantitative analysis.

Specific gravity and relative density tests were performed on three small lunar soil samples that were made available to us. Preliminary test results are as follows:

Sample No.	Specific Gravity	Minimum Bulk Density g/cm^3	Maximum Bulk Density g/cm^3
14163, 148	2.95	.9	1.5
14259, 3	2.95 ± .03	.9	1.5
15601, 82	3.18 ± .02	1.1	1.85

These tests will be repeated and the particle size distributions will also be determined.

PLANNED RESEARCH

Mechanical properties (strength, compressibility, modulus of deformation and anisotropy) associated with different fabrics of crushed basalt simulant will be determined. It will be attempted to characterize fabric in terms of mechanical properties. The testing of smaller lunar soil samples will be continued. The accumulated data on particle size, shape and distributions can then be used to infer interrelationships between lunar history and processes, fabric and mechanical properties.

LUNAR SOIL SIMULATION STUDIES—BEHAVIOR UNDER STATIC LOADING

by

Patrick M. Griffin and William N. Houston

OBJECTIVES

The objectives of the lunar soil simulation studies are:

1. To use all available data from previous lunar missions as a guide in preparing lunar soil simulants which behave mechanically like the actual lunar soil.

2. To determine the mechanical properties of these simulants and to use these properties in analyses which will facilitate the assessment of actual lunar soil behavior under a variety of loading conditions which may be encountered during future exploration of the moon.

STATUS

Plane Strain Tests

Plane strain tests are being performed on LSS No. 3 (described in the last Semiannual Status Report) in an effort to assess the effect of gradation on the mechanical properties. As the Apollo 16 mission has again confirmed, the gradation of actual lunar soil is somewhat variable. Thus a single simulant with a particular gradation cannot adequately represent the range of gradations encountered on the lunar surface. When the plane strain tests on LSS No. 3 are completed, quantitative relationships will be generated which will adequately define the variation of mechanical properties for the variety of gradations which have been observed and which might be expected for actual lunar soil.

Although the plane strain testing program is not yet complete, sufficient data have been generated to make some preliminary comparisons between the strengths of LSS No. 2 and LSS No. 3. It was expected that the somewhat coarser LSS No. 3 would tend to exhibit higher strengths under similar loading conditions than would LSS No. 2. As evidenced in the preliminary comparisons presented in Figure 1, that qualitative prediction does appear to be correct.

In order to make a valid comparison between the strengths of the two simulants, it was necessary to compare strengths under comparable loading conditions. The curves presented in Figure 1, therefore, compare the deviator stress at failure for the two simulants at the same confining pressure and at the same initial relative density. For the purposes of this comparison, the deviator stress at failure is defined as the maximum deviator stress to occur within 10% strain, because many of the loose specimens exhibited gradually rising stress strain curves which did not peak, even at strains as high as 20%. Alternative failure criteria for these specimens will also be considered.

One-Dimensional Compression Test Results

A series of one-dimensional compression tests were performed on samples of LSS No. 3 for various values of initial void ratio, as was done for LSS No. 2. The results of this test series are plotted in Figure 2. These results are especially useful for computation of probable soil density profiles on the lunar surface. Such profiles will be developed subsequently.

Plate Load Tests

Plate load tests have been completed on loose, medium dense, and dense soil deposits of LSS No. 3, and the results have been presented in
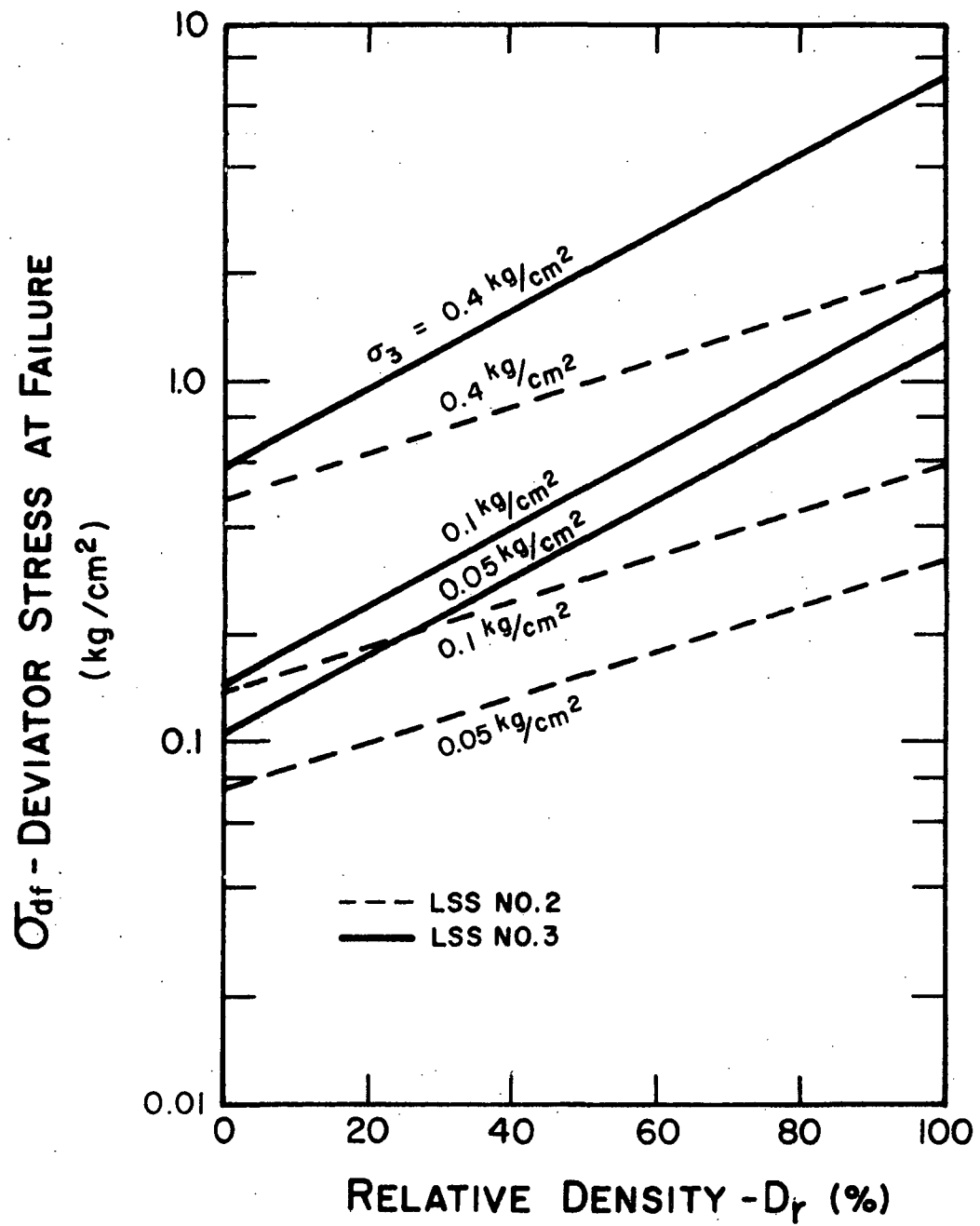
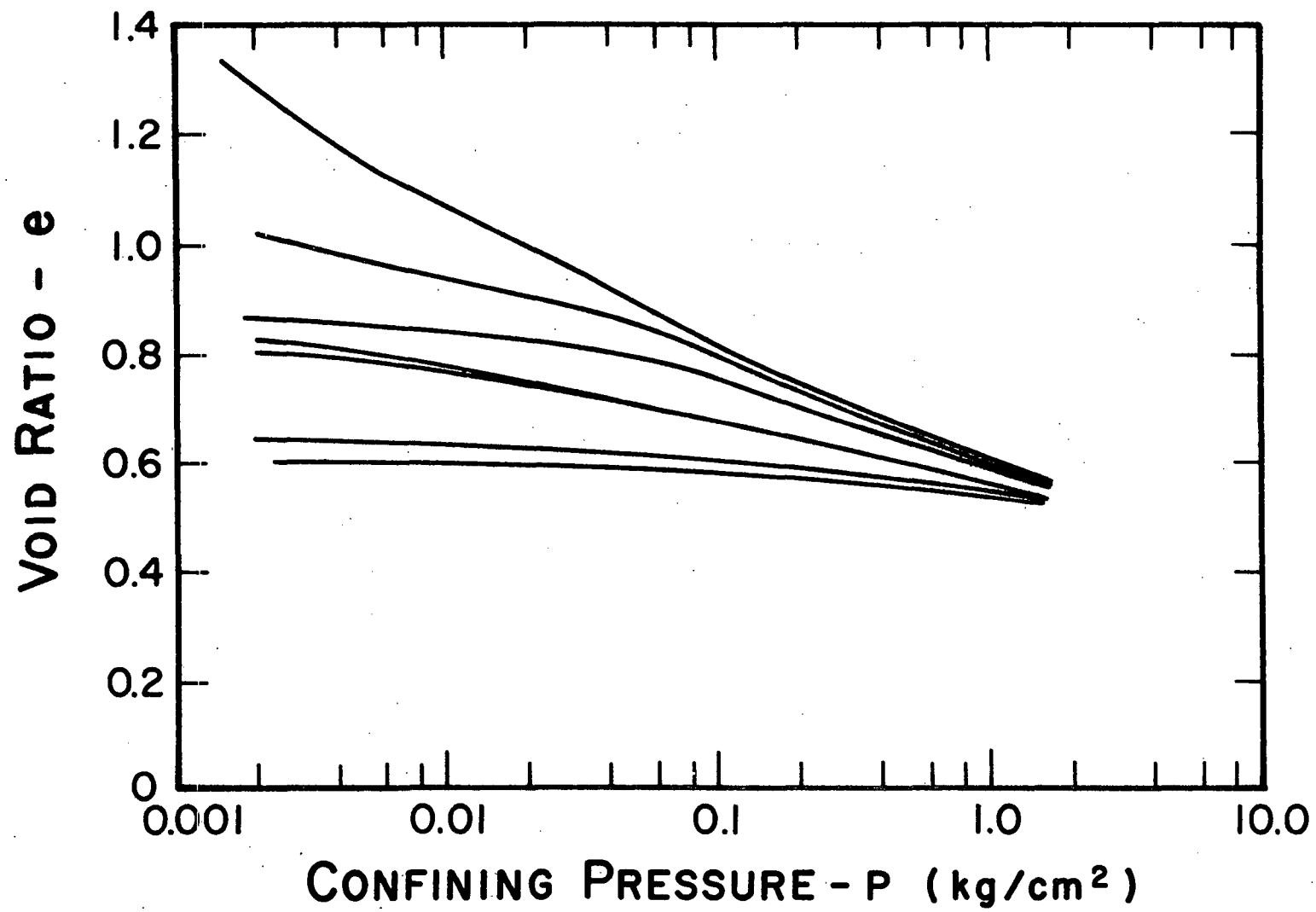Fig. 1. Preliminary comparison of plane strain tests on LSS No.'s 2 and 3

Fig. 2. One-dimensional compression test results, LSS No. 3, w ≅ 2.0%

the two previous semiannual status reports (June, 1971, and January, 1972). Further testing and analysis will be delayed until results of the plane strain testing program become available.

PLANNED RESEARCH

The study of the behavior of LSS No. 3 under static loading will continue as follows:

1. Completion of the plane strain testing program now in progress. The test data will be used to obtain mathematical expressions for the stress strain and strength parameters, as was done for LSS No. 2.

2. Computation of probable lunar surface soil density profile (density variation with depth) for soils with gradation similar to that of LSS No. 3.

3. Comparison of measured plate load test curves and predicted curves obtained by use of the stress strain and strength parameters in the finite element computer program developed for analysis of LSS No. 2. This comparison will be used to validate the use of the computer program, together with measured soil properties, to describe the behavior of LSS No. 3 under various types of static loading, as was done for LSS No. 2.

4. When testing and analysis are complete and the accuracy of the finite element solution has been verified for LSS No. 3, the method will be applied to the analysis of the two plate load tests done on the lunar surface during the Apollo 16 mission and to the solution of typical problems which may arise during Apollo 17 or subsequent exploration of the lunar surface.

LUNAR SOIL SIMULATION STUDIES—BEHAVIOR UNDER DYNAMIC LOADING

by

Yoshiharu Moriwaki and William N. Houston

OBJECTIVES

The objectives of the dynamic loading simulation studies are:

1. To obtain quantitative data on the response of one or more lunar soil simulants under dynamic loading. These data are to include the variation of stress strain parameters as functions of initial soil conditions such as void ratio and confining pressures.

2. To organize these data in a form which is useful for application to lunar surface dynamic loading problems.

STATUS

The simple shear dynamic testing program using Lunar Soil Simulant No. 2 (LSS No. 2), described in the last status report is essentially complete, and reduction of the data is now underway. Some preliminary results are shown in Figures 3, 4 and 5. Quantities shown in these figures are defined in Fig. 6.

As anticipated, the dynamic properties of LSS No. 2 (characterized by equivalent shear modulus, hysteretic damping ratio and vertical strain) appear to depend heavily upon initial soil density, confining pressure, and shear strain amplitude.

A preliminary comparison of the dynamic properties of LSS No. 2 with similar data available for ordinary "terrestrial" sands (Hardin and Drnevich, 1970; Seed and Idriss, 1970; Silver and Seed, 1969), which
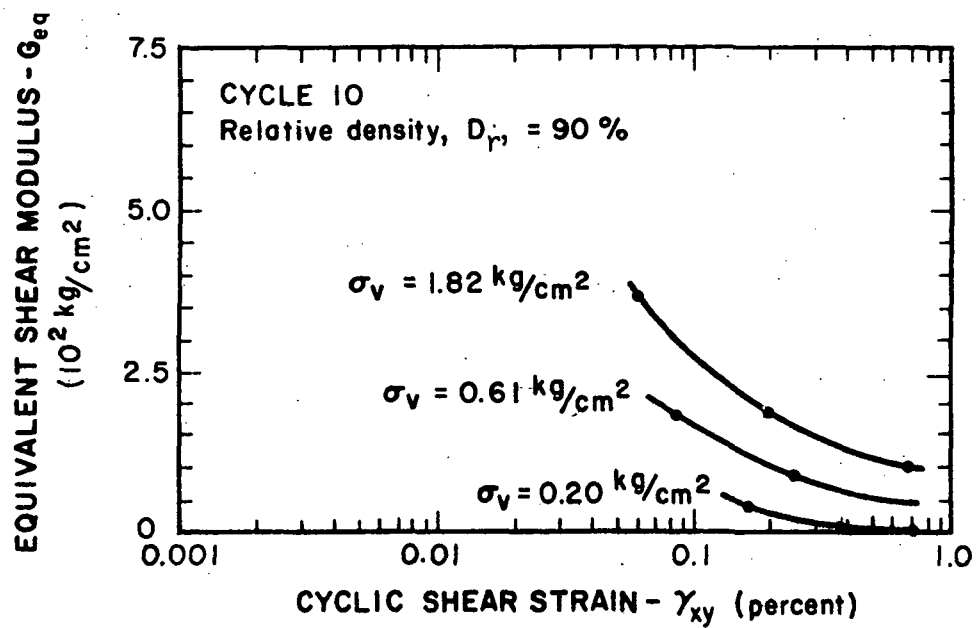
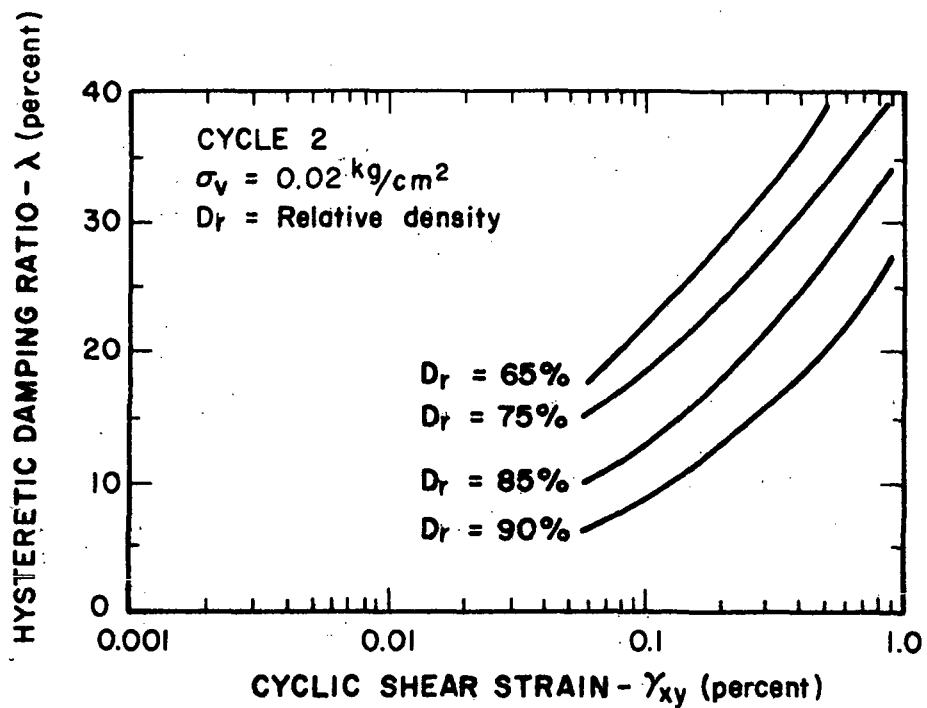Fig. 3. Effect of vertical stress on shear modulus in tenth loading cycle

Fig. 4. Effect of relative density on hysteretic damping
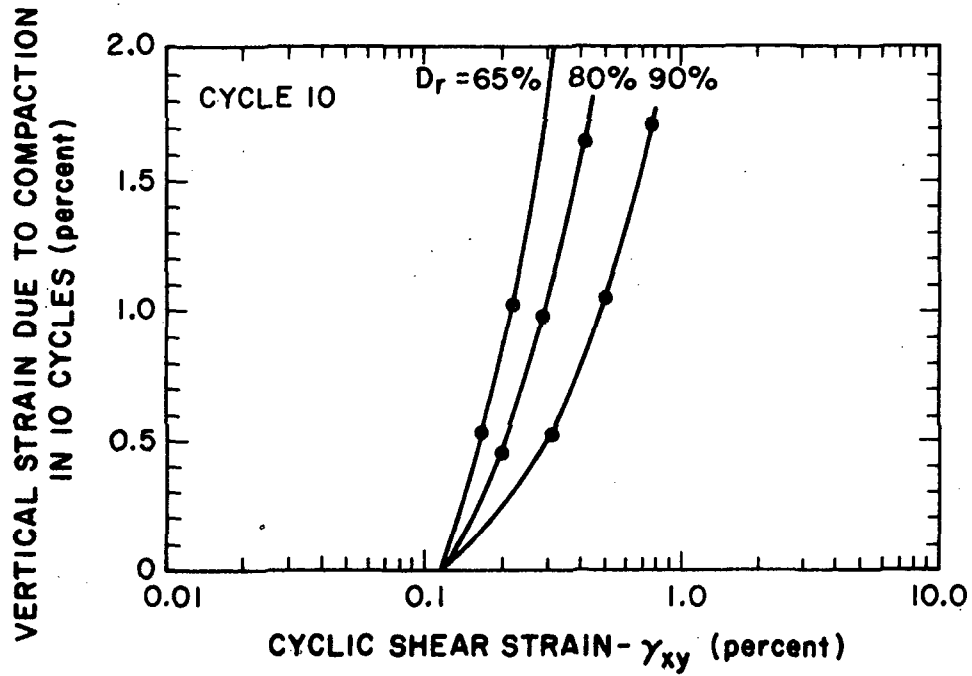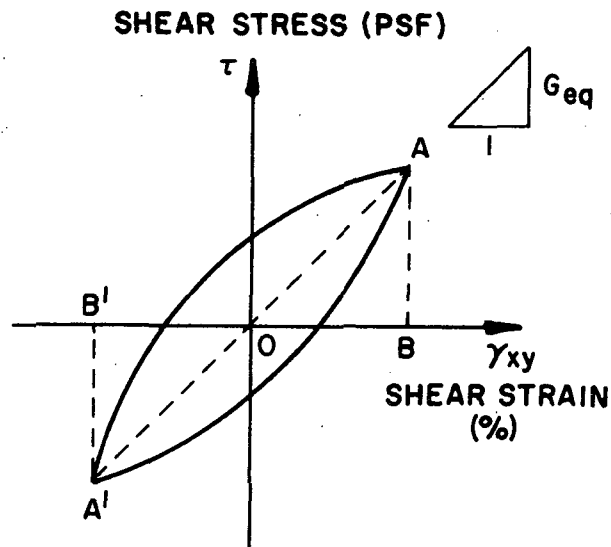
Fig. 5. Effect of relative density on settlement in ten cycles

Equivalent shear modulus $= G_{eq} = \dfrac{\tau_{max}}{\gamma_{xymax}} = \dfrac{\overline{AB}}{\overline{OB}}$

Hysteretic damping ratio $= \lambda_n = \dfrac{\text{Area of hysteresis loop}}{2n\,(\text{area of triangles OAB and OA'B'})}$

Fig. 6. Typical hysteresis loop

are typically somewhat coarser and more uniform, has been made and makes possible the following observations:

1. For the range of shear strain levels tested (somewhat below 0.1% and higher), the equivalent shear modulus of LSS No. 2 appears to be much lower than most ordinary sands.

2. Unlike most sands, hysteretic damping ratio of LSS No. 2 seems to be highly dependent on initial relative density of the soil.

3. For a given shear strain level, vertical strain (compression) in LSS No. 2 appears to be much higher than for sands, but no densification occurred for a shear strain level lower than about 0.1%.

4. In spite of these differences, the general trend of the functional dependency of dynamic properties of LSS No. 2 on input parameters seems to be consistent with what has been observed previously for other soils.

It has been tentatively hypothesized that the low dynamic shear moduli for LSS No. 2 relative to coarser and more uniform sands arise from the differences in gradation, which influences the compressibility.

Although a quantitative comparison will be delayed until the results of a planned series of resonant column tests become available, it is of interest to note that the "unusually low" shear moduli obtained for LSS No. 2 are qualitatively consistent with the "unusually low" seismic velocities measured on the lunar surface (Carrier et al., 1972; Kovach and Watkins, 1972).

Based upon the preliminary results of simple shear dynamic testing program, some further modifications of resonant column dynamic testing

equipment were deemed necessary and are now underway. These include the reduction of sample size to insure the uniformity of initial specimen conditions. Necessary equipment modifications are almost complete and the testing program itself should begin shortly.

PLANNED RESEARCH

Dependency of the dynamic properties of the lunar soil simulants on grain size and gradation will be investigated by testing a coarser-grained simulant.

The resonant column testing program will be completed to obtain the dynamic properties of LSS No. 2 in the low strain range ($\sim 10^{-3}\%$).

Data obtained from these tests will be reduced, summarized, and presented in a usable form for application to various dynamic problems which may arise on the lunar surface. Attempts to compare and correlate these results with data from Apollo missions (e.g., active and passive seismic data) and with previous results of terrestial soils will also be made.

TERRESTRIAL MODELING OF LUNAR SOIL BEHAVIOR

by

Donald D. Treadwell and James K. Mitchell

OBJECTIVES

Lunar surface penetration data in the form of force–penetration curves have been obtained by the self-recording penetrometer (SRP) during the Apollo 15 and 16 missions. To determine the in situ lunar soil properties from these penetration test results (or from other objects pushed into the lunar surface), accurate reproduction of these lunar curves on earth under controlled conditions is desirable. Gravity effects are known to be important in controlling the stress, deformation, and strength behavior of soils representative of those on the moon, because the strength of such soils is mainly frictional; thus, soil weight influences behavior directly. Modeling techniques provide one possible means of accounting for the gravity differences between the lunar and terrestrial environments. The objectives of the modeling research are therefore to:

1. Determine the appropriate modeling laws and scale factors to be used for terrestrial simulation of soil behavior on the moon.

2. Reproduce and analyze lunar surface penetration curves obtained on the moon under controlled laboratory conditions on earth.

3. Further quantify the effect of such variables as gravity, soil porosity and compressibility, and penetrometer type on penetration resistance.

4. Establish the general validity of modeling to simulate the effects of different gravity fields on soil behavior. If this can be done successfully, then terrestrial simulations of different

planetary fields (e.g., Mars) may be possible.

STATUS

The particular form of modeling (scaling) proposed for the evaluation of the properties of soil on the moon using lunar soil simulants on earth was presented in the last status report, and work done to that time was described. Progress during the present reporting period has been limited because of the need to concentrate effort on preparation for and data analysis from the Apollo 16 mission.

PLANNED RESEARCH

The validity of the proposed modeling relationships will be investigated experimentally by means of controlled static penetration resistance tests. Test soils will be prepared at various porosities and penetrated using penetrometer tips of various sizes and shapes. The data obtained will be analyzed in terms of the appropriate failure mode as well as the expected modeling laws and scale factors.

The proposed experimental work will be extended to include compressible deposits and layered deposits. Also, the penetration resistance developed at large depths (depth/width >20) will be investigated.

IMPACT PENETRATION IN LOW-COHESION SOILS

by

James B. Thompson and James K. Mitchell

OBJECTIVES

The objective of this investigation is to develop techniques by which low-velocity (0-200 fps) impact penetrometers may be used to determine soil properties, particularly in extraterrestrial environments. The following specific objectives for achieving this goal are:

1. Development of an improved understanding of soil deformation during impact penetration, and determination of the effects of various combinations of soil properties on the response of impact penetrometers.

2. Development of theoretical and empirical relationships between soil properties and penetrometer response.

3. Delineation of the factors which must be considered in the extrapolation of terrestrial test results to a lunar environmnet and the derivation of the relationships needed to make this extrapolation.

STATUS

The state of the art of impact penetration of soils has been critically reviewed and was reported in detail in Vol. I of our Final Report, "Lunar Surface Engineering Properties Experiment Definition," Space Sciences Laboratory Series 11, Issue 48, July 1971. It was concluded that a controlled experimental program is required to attain the above objectives.

This experimental program consists of impacting a cone-tipped cylindrical penetrometer into low-cohesion soil targets of varying properties in both terrestrial atmospheric and vacuum environments. The primary outputs from each impact test include:

1. The properties of the soil target

2. The prevailing air pressure

3. The impact velocity of the penetrometer

4. A record of the deceleration of the penetrometer versus time following the impact

5. The total depth of penetration of the penetrometer

6. Measurements of the soil deformation pattern.

The equipment necessary to conduct the atmospheric environment phase of this experimental program has been designed, fabricated, and installed. The major components of this equipment include a compressed-air gun, a photocell equipped velocity trap, a penetrometer instrumented with a piezoelectric accelerometer, an oscilloscope, a soil target box, and various items used to construct the soil targets. The same equipment, with minor modifications, will be used to conduct the vacuum environment phase of the program. The desired vacuum levels within the soil targets will be achieved utilizing a vacuum chamber located at Ames Research Center.

An investigation into techniques for processing and placing the soil to be used as the target was conducted. The primary purpose of this investigation was to develop methods by which uniform soil targets could be constructed. Several techniques were investigated including vibration, placing the sand by pouring through sieves, and spreading sand in a manner similar to spreading grass seed. It has been found that vibratory methods yield uniform targets of dense soil, and this technique is being

used to construct dense soil targets. Targets of uniform intermediate density are being constructed by pouring sand on a screen located at a calibrated distance from the surface of the target. Uniform, loose soil targets are being constructed by drawing a screen through the sand target.

At this time, the atmospheric environment phase of this experimental program has almost been completed. Testing of loose and dense soil targets has been finished and only a few tests of intermediate density soil targets remain. Approximately twenty-five tests have been conducted and all results seem to be consistant with known behavior of soil. A portion of the results generated from this research has been published in proceedings of a conference on Rapid Penetration of Terrestrial Materials held at Texas A&M University on February 1-3, 1972 (Thompson and Mitchell, 1972).

PLANNED RESEARCH

In the near future, the atmospheric environment testing will be completed. Tests under a vacuum environment will then be conducted. Concurrently, theoretical and emperical relationships between soil properties, environmental conditions, and penetrometer response will be developed.

TRAFFICABILITY AND LUNAR TERRAIN INVESTIGATIONS

by

H. John Hovland and James K. Mitchell

OBJECTIVES

The objectives of this research are:

1. To develop a wheel-soil interaction analysis method based on the basic soil parameters, cohesion (c), friction angle (ϕ), and density (ρ).

2. To compare and reconcile this method with existing methods.

3. To evaluate the usefulness of the developed method for interpreting wheel-soil interaction in the lunar terrain.

STATUS

Research conducted during this reporting period has emphasized:

1. Evaluation of existing wheel test data.

2. Development of a rational method for predicting wheel-soil interface stresses.

Evaluation of existing wheel test data has continued in an effort to ascertain the usefulness of such data for the development of general wheel-soil interaction theory. Certain trends are emerging.

The desired performance parameter in the design of traction wheels is the drawbar pull, P. This is defined as the pull that can be developed from the traction of a given wheel on a given soil for certain input torque, T. Frequently this parameter is plotted as P/W (W = wheel load) against slip, s. Our studies (reanalysis of data by Leflaive, 1967) show that it is more meaningful to recognize a performance surface as illustrated in Fig. 7. As shown by Fig. 7 there is a separate P vs. s relationship for each value of W.
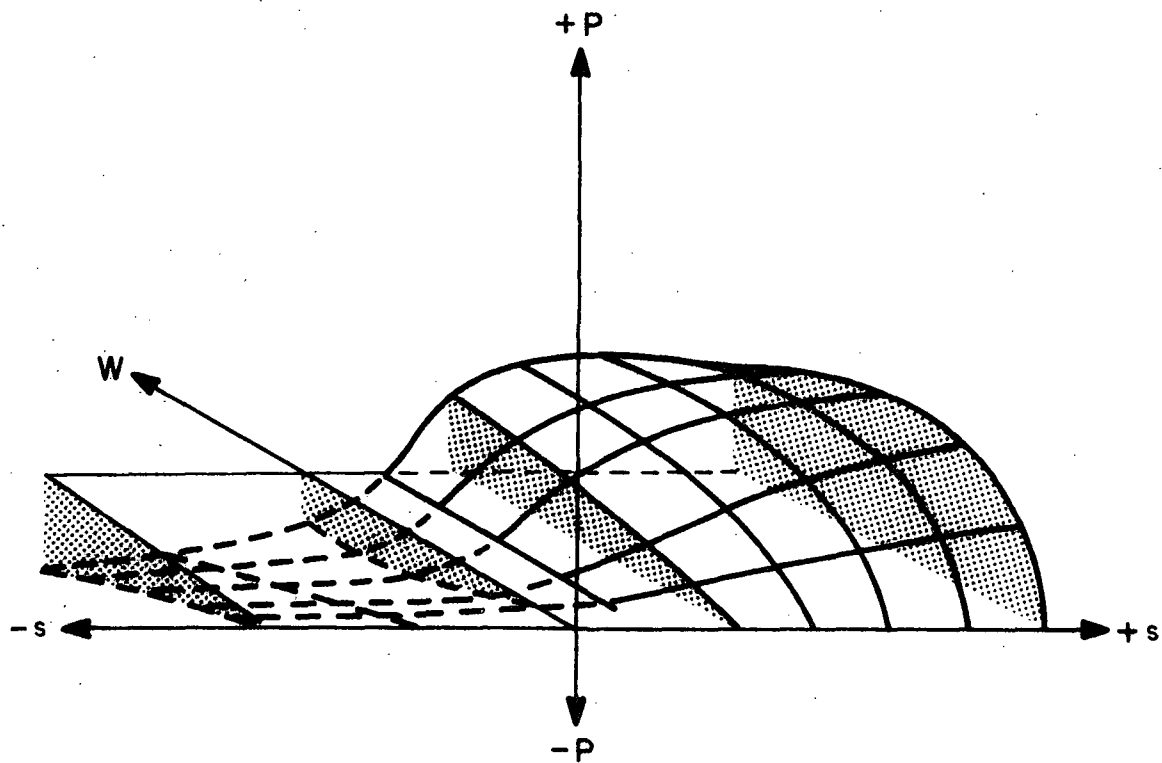
Fig. 7. Performance surface; Pull as a function of wheel load and slip

Fig. 7 also indicates why existing data are of limited value in developing general wheel-soil interaction theory; each different wheel geometry, wheel load and soil condition will lead to a different P vs. s relationship. The complexity of the general problem has been recognized for a long time, and for this reason perhaps experiments have usually been conducted for special cases of wheel and soil conditions. Therefore, the data tend to be at best spotty (for a limited portion of the performance surface only) or at worst incomplete (lacking in the description of all necessary test conditions).

The concept of performance surface illustrates the scope of the problem that must be attached by a general wheel-soil interaction theory. A similar surface results for torque and will lie above the P-surface. For the sake of simplicity, this torque surface and other energy considerations are not discussed in this status report.

Efforts to develop a rational method for predicting wheel-soil interface stresses have continued. It appears that an approximate solution can be obtained by an approach such as described in our last semiannual status report. Except for large values of slip, however, for which the soil shear strength is fully mobilized, it appears that the tangential and radial stresses at the wheel-soil interface are not closely related. The complexity of this phenomenon is illustrated in Figures 8 and 9. Figure 8 shows the tangential, τ, and radial, σ, stresses at a wheel-soil interface for high positive slip (a forward spinning wheel). Figure 9 shows the ratio of τ/σ for all values of contact angle θ, and slip, s.

Conditions are known for certain values of slip for the stress ratio surface illustrated in Fig. 9. For example, a towed wheel operates at zero torque, assuming that friction at the hub is insignificant, and therefore
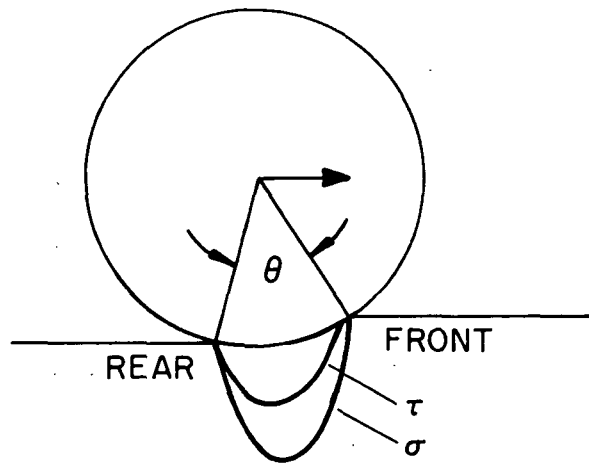
Fig. 8.   Stresses at a wheel-soil interface
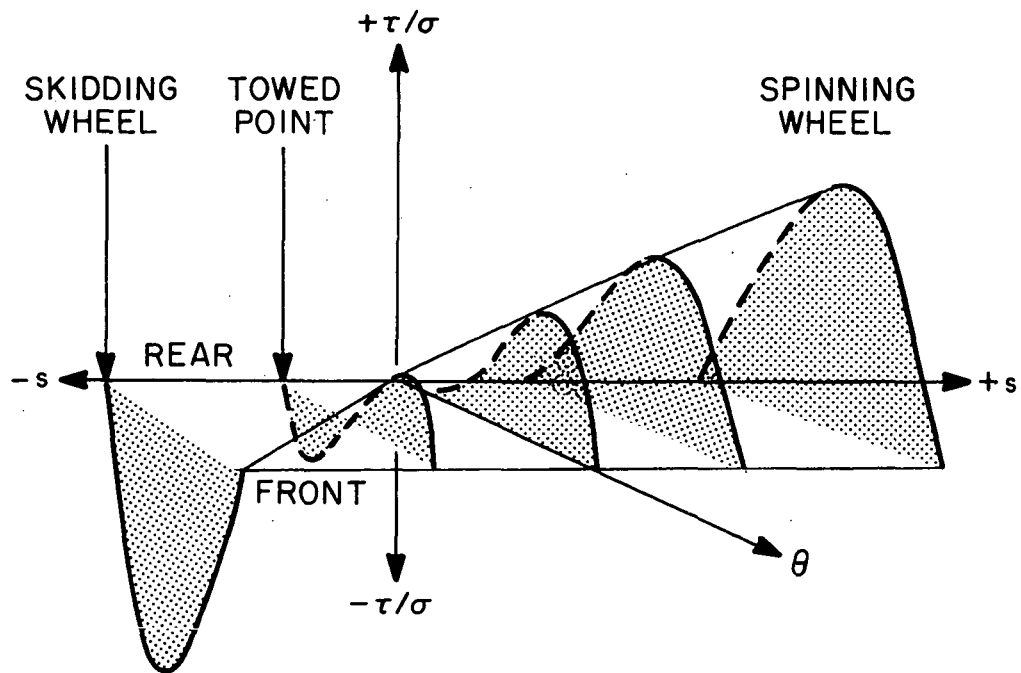(high positive slip)

Fig. 9.   Stress ratio surface; Shear stresses mobilized
along the wheel-soil interface

the negative and positive shear forces for this condition are equal. A freely rolling sphere rolling at constant velocity would also satisfy this condition. At high slip (positive or negative) the shear stresses would be fully mobilized and related to the radial stresses as perhaps by the Mohr-Coulomb equation. Except for these special conditions and limited scattered data, the general conditions illustrated by the stress ratio surface are essentially uninvestigated and the phenomenal relationships undefined.

PLANNED RESEARCH

The above studies will be continued with an emphasis on:

1. Completing and evaluating a wheel-soil interaction theory.

2. Completing and evaluating a method for predicting wheel-soil interface stresses.

3. Evaluating the results with respect to a contribution to the wheel-soil interaction phenomenon in general, and specifically with respect to wheel-soil interaction in the lunar environment.

COMPLETED RESEARCH

GAS PERMEABILITY OF POROUS MEDIA

Studies into gas permeability of porous media have been completed, and the results are presented in a final research report (Hurlbut and Jih, 1972), which was previously submitted.

STATIC PENETRATION RESISTANCE IN LOW-COHESION SOILS

Studies on the static penetration resistance in low-cohesion soils (H. T. Durgunoglu and J. K. Mitchell), have been completed and a separate final research report will be prepared. Detailed results are given in H. T. Durgunoglu's Ph.D. dissertation, recently completed, and an abstract of this research is given below.

Abstract:

Model test results have been used to define the failure mechanism associated with the static penetration resistance of cohesionless and low-cohesion soils. Knowledge of this mechanism has permitted the development of a new analytical method for calculating the ultimate penetration resistance which explicitly accounts for base apex angle and roughness, soil friction angle, and the ratio of penetration depth to base width. Curves relating the bearing capacity factors N_c and $N_{\gamma q}$ to the soil friction angle are presented for failure in general shear.

Strength parameters and penetrometer interaction properties of a fine sand were determined and used as the basis for prediction of the penetration resistance encountered by wedge, cone, and flat-ended penetrometers of different surface roughness using the proposed analytical method. Because of the close agreement between predicted values and values measured in laboratory tests, it now appears possible to deduce in-situ soil strength

parameters and their variation with depth from the results of static penetration tests.

A procedure for determining the soil cohesion and friction angle from the results of static penetration tests is proposed. This procedure is illustrated by application to model test results, to penetration data presented by other investigators, and to penetration data obtained for the luner surface by the Apollo 15 self-recording penetrometer and the Soviet Lunar Rover Lunokhod-1.

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[3] Hurlbut, F. C. and Jih, C. R., "Flow in Porous Media Under Rarefied Gas Conditions," final report for research phase: Fluid Conductivity of Lunar Surface Materials, NASA Grant NGR 05-003-406, University of California, Space Sciences Laboratory Series 13, Issue 43, May 1972.

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PUBLICATIONS

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2. Houston, W. N. and Namiq, L. I., "Penetration Resistance of Lunar Soils," Proc. of the ISTVS-TRW Off-Road Mobility Symposium, Los Angeles, California, Nov., 1970, p. 2.

3. Hovland, H. J. and Mitchell, J. K., "Pressure Distribution and Soil Failure Beneath a Towed, Rigid, Spherical Wheel in Air Dry Sand," Proc. of the ISTVS-TRW Off-Road Mobility Symposium, Los Angeles, California, Nov., 1970, p. 107.

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