UNCLASSIFIED

AD NUMBER

AD-872 690

NEW LIMITATION CHANGE

TO

Approved for Public Release;
Distribution Unlimited.
** St'mt: A
** Code: 1

FROM

N/A

AUTHORITY

USNPS Ltr, 14 Feb 1968

THIS PAGE IS UNCLASSIFIED

REPRODUCTION QUALITY NOTICE

This document is the best quality available. The copy furnished to DTIC contained pages that may have the following quality problems:

- Pages smaller or larger than normal.
- Pages with background color or light colored printing.
- Pages with small type or poor printing; and or
- Pages with continuous tone material or color photographs.

Due to various output media available these conditions may or may not cause poor legibility in the microfiche or hardcopy output you receive.

☐ If this block is checked, the copy furnished to DTIC contained pages with color printing, that when reproduced in Black and White, may change detail of the original copy.

AFFDL-TR-70-30

AIRCRAFT SURFACE OPERATION — SOIL SURFACE CORRELATION STUDY

DAVID C. KRAFT

J. RICHARD HOPPENJANS

University of Dayton Research Institute

TECHNICAL REPORT AFFDL-TR-70-30

JUNE 1970

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics Laboratory (FDFM), Wright-Patterson Air Force Base, Ohio 45433.

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

300 - July 1970 - CO455 - 125-2752

AIRCRAFT SURFACE OPERATION — SOIL SURFACE CORRELATION STUDY

DAVID C. KRAFT

J. RICHARD HOPPENJANS

University of Dayton
Research Institute

FOREWORD

This report was prepared by the Aerospace Mechanics Group of the University of Dayton Research Institute under U.S. Air Force Contract F33615-70-C-1019. The contract was initiated under Project no. 1369, "Mechanical Subsystems for Advanced Military Flight Vehicles," Task no. 136908, "Military Air Vehicle Landing Gear/Surface Interaction Criteria." This work was conducted under the direction of the Vehicle Equipment Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, Mr. George Sperry (FDFM), Project Engineer.

This report covers work conducted from 15 August 1969 to 15 February 1970.

Appreciation is expressed by the authors to Mr. Sperry who provided the major part of the literature which was reviewed,and channeled the efforts toward Air Force flotation objectives. This report was submitted by the authors in February 1970.

Publication of this technical report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

K. H. Digges

KENNERLY H. DIGGES
Chief, Mechanical Branch
Vehicle Equipment Division
Air Force Flight Dynamics Laboratory

ABSTRACT

Ultimate goals of Air Force landing gear/soil interaction research are to develop maximized landing gear design criteria for aircraft operation on soil surfaces and to establish absolute techniques for the prediction of military aircraft operational capability at any soil surfaced site. In order to achieve these goals, real life relationships must be established between aircraft surface operational capability, and soil and site characteristics.

This program was concerned with the identification of both soil and site parameters usable for defining aircraft operations capability. The research effort included a literature survey, a review of existing rapid in situ and remote sensing techniques for determining soil strength and ground roughness, and a study of the proposed active landing gear system as related to the required soil and site parameters. A detailed description of each of the reviewed rapid in situ and remote sensing techniques is included.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF SYMBOLS

AI	Airfield Cone Index Value
B	Difference in horizontal position between photographs
C	Empirical constant
c	Apparent cohesion
CBR	California Bearing Ratio
CI	Mobility Cone Index value
CRT	Cathode ray tube
CW	Continuous wave
D	An index related to the vertical position of the PSD curve at a frequency of 2π radians/ft.
f	Camera focal length
H	Height of camera above terrain
K	Dispersion factor (Equation 3)
K	Tangent modulus of deformation
k_c	Empirical constant used in Bekker's sinkage equation
k_ϕ	Empirical constant used in Bekker's sinkage equation
m_h	Amount of error in a spot elevation determination from airphotos
m_x	Empirical error determination
N	Empirical constant (Equation 1)
N	An index related to the horizontal position of the PSD Curve at a spectral density of 1.0 in^2/radians/ft.

N	Number of observation triangles (Equation 3)
n	Exponent of sinkage in Bekker's sinkage equation
PSD	Power spectral density
$P(\Omega)$	Power spectral density of the surface profile height
Q	Roughness parameter
R1	Vector strength
RI	Remolding index value
RCI	Rating cone index
SLR	Side look radar
σ	Variance which equals the integral on frequency of the PSD
ϕ	Angle of internal friction
Ω	Spatial frequency

SECTION I

INTRODUCTION

The effective and efficient operation of Air Force aircraft from soil surfaced sites is dependent upon providing aircraft with maximized landing gear systems and the ability to predict aircraft operational capability at any soil surfaced site. A maximized landing gear system will minimize dynamic loads induced into the aircraft and provide capability to achieve the maximum number of operations required at specified minimum soil surface site conditions. Moreover, a maximized system must have a minimum total and related structural weight, and require the smallest stowage space possible. Effective use of aircraft can be made only if aircraft operational capability at each soil surfaced site to be used can be established on an absolute basis.

In order to develop maximized landing gear criteria and establish absolute techniques to predict aircraft operational capability at soil surfaced sites, real life relationships must be developed between landing gear surface operation capability and soil surface and site parameters. Therefore, the objective of this study, on a preliminary basis, was to obtain a general understanding and to identify soil and site parameters related to landing gear operation capability. Also, the study provides a review of existing methods for determining these parameters.

The research effort included a literature search, an identification and recommendation of both soil and site parameters, and a review of existing rapid in situ and remote methods for determining these parameters. A portion of the study was devoted to relating the current state-of-the-art of remote and in situ measurement of soil and site parameters to the development of an active landing gear system. Descriptions of in situ and remote evaluation techniques and applicable reference reports are provided in Appendix C. Only unclassified material was reviewed for this program.

In reviewing literature searches from DDC, NASA, and other sources, approximately 1000 titles and/or abstracts were screened and, of this total

generalizations made from the

110 appear in Appendix A, with a cross index. In addition to this Appendix, there is considerable literature that reports using either in situ or remote sensing devices. These articles, however, either did not discuss the devices directly or were references which gave only examples of specific applications of remote sensors. Consequently, this type of article provided no basic insight into the problem of aircraft surface operation research as related to either in situ or remote sensing and therefore was not included in the list.

To supplement the literature review with the most current information on in situ soil testing techniques, an information request was sent to twenty-two governmental, educational, and industrial organizations who were identified as knowledgeable in the rapid in situ and remote sensing areas. A copy of this request, which is included as Appendix B, was sent to each organization subsequent to a personal phone call from the University of Dayton Research Institute. This information request asked each organization to comment on the methods listed, to write in any method not listed that might be applicable, and to evaluate current methods of in situ rapid testing and remote sensing of soil properties which will define soil properties applicable to aircraft flotation and operation on soil surfaces.

SECTION II

RAPID IN SITU SOIL MEASURING TECHNIQUES

1. Method Identification

Among the many methods of evaluating soil properties in situ for analysis of aircraft flotation and surface operation capability, eight were selected from the literature as being either the most feasible or the most currently used. Of the eight, all but two report a soil strength that is obtained through some type of penetration test. All but one define some strength parameter. These eight methods are:

- Mobility Cone Penetrometer
- Airfield Cone Penetrometer
- California Bearing Ratio
- Bevameter Bearing and Shear Devices
- Remolding Index
- Sheargraph
- Nuclear Methods
- Dimensional Analysis for Relating Military Vehicle Ruts to Aircraft Flotation Capacity

The nuclear devices and the sheargraph do not measure a penetration type of strength and the former does not measure strength at all. Strength can only be inferred from the moisture content and density as measured with the nuclear devices. Each of the methods listed and a few other related methods are described in detail in Appendix C. Included in this description is a reference which will serve as a prime source of information for that method. Note that the Mobility Cone, Airfield Cone, and Remolding Indices are very closely related and may be considered either as one system or three separate methods as listed.

2. Organizational Review -- Rapid In Situ Results

Twelve organizations responded to a request to review, comment on, and rate rapid in situ techniques for the determination of soil strength. Appendix B provides a list of participating organizations, the request letter used, and Information Summary Sheets. Table 1 provides a summary of the ratings given to the in situ techniques considered.

The comments on each of these methods were somewhat repetitive, therefore only a condensed list is presented below. For convenience they are grouped by method.

Mobility Cone and Airfield Index:

- Is simple to operate and easy to reduce data
- Gives soil profile with depth
- Gives good correlation of data
- Measures a small loading area
- Does not measure a fundamental soil property
- Is not applicable to high strength soil

California Bearing Ratio:

- Is a well-known test
- Gives good correlation of data
- Measures only surface properties
- Requires heavy equipment and is time consuming
- Requires excavation to get a depth profile

Bevameter:

- Attempts to measure a fundamental soil property
- Presently gives no correlation to aircraft flotation
- Boundary conditions not defined
- Data reduction difficult
- Measured strength consistently too low

Table 1. Organizational Review and Rating of In Situ Techniques.

Method \ Response No.	1	2	3	4	5	6	7	8	9	10	11	12	Weighted Average
MOBILITY CONE		2	2	1	1	1	1	3	1	1	3	2	1.6
AIRFIELD INDEX		1	2	1	1	1	1	2	4	2		2	1.7
CALIFORNIA BEARING RATIO			2	3	3	2	2	1	2	3	4	4	2.6
BEVAMETER SHEAR			3		4	7		2	5	8	1	3	4.1
BEVAMETER BEARING			2		2	4		2	3	7	1	3	3.0
REMOLDING INDEX			2				4	3	7		3	4	4.6
SHEARGRAPH			3			6			6	4	2	9	5.0
NUCLEAR METHODS			2	2		5	5	4	9	6	5		4.8
Dimensional Analysis (Military Vehicle to Aircraft Flotation Capacity)			2			3	3	1-2	8	5	6	1	3.7

RATING KEY: Methods are rated in order of preference (i.e., 1-best, 2-next best, ... 9-least acceptable). Blank blocks indicate that no rating was given in the response.

Remolding Index:

Gives a possible multipass correlation

Sheargraph:

Is easy to operate

Boundary conditions are unknown

Data is instrument dependent

Presently gives no correlation to aircraft flotation

Measures a small loading area

Nuclear:

Is rapid and nondestructive

Presently gives no correlation to soil strength

Needs calibration for each soil type

Dimensional Analysis (Military Vehicle to Aircraft Flotation Capacity):

Presently gives no correlation to aircraft flotation

Has limited prediction capability

In addition to personal comments on different methods, some respondents listed other methods they thought would be of interest. These are as follows:

Penetro-Shear:

Apparently a method of testing such that both shear and bearing properties can be measured concurrently.

"The Penetro-shear Apparatus", Tech. Report No. 10332, U.S. Army Tank-Automotive Center, Warren, Mich., July 1968.

Soil Truss:

A method of measuring shear strength under a large loading area.

Tech. Mem. M-003, U.S. Naval Civil Engineering Lab, Port Hueneme, California.

Evans Shear Vane:

Measures shear strength.

"Measurement of Surface Bearing Capacity of Soil", Geotechnique Vol. II, June 1950.

Plate Bearing:

Allows evaluation of soil properties using larger loading areas. This is a common method to most engineers.

Seismic:

These devices have responses that are related to stiffness but the data has not been fully developed into a suitable correlation for actual use.

Vibratory:

A method under development that will hopefully give a value of the shear modulus of soil.

The above six methods are generally obscure except, of course, for plate bearing. They are not, for various reasons, applicable to the tire/soil interaction problem.

3. Results

Based on the review of literature and the organizational review, the cone penetration type test (either Mobility or Airfield) is presently the best rapid method of assessing the soil strength for the prediction of aircraft soil surface interaction phenomena. The first cone penetrometer was developed by the Waterways Experiment Station for mobility research and testing. Since that development by WES, the penetrometer has been very popular in evaluation testing of aircraft for flotation on unprepared airfields. Most of this testing was reported using CBR values, and as a consequence, there are many correlations relating flotation and CBR values. Upon reviewing some of these earlier tests, it was noticed that many of the CBR values were obtained through a correlation of CBR vs Airfield Index values. Thus, most of the field testing of soil strength in the past has been done with a cone penetrometer and therefore there is a good correlation between aircraft performance and cone penetrometer values. In addition to the above, the cone penetrometers, either the airfield or mobility type, are simple to operate, easily carried by one man for field use, and permit quick data reduction.

The major drawbacks of the penetrometer include operator error which decreases reliability, need for individual calibration to be able to accurately relate cone penetration values to CBR, need for repetitive tests to establish a realistic average soil strength index and other minor operational problems as noted in Appendix C.

Another promising method, presently in an initial evaluation stage, is an empirical correlation between the measured rut depth of a standard military truck tire and the flotation performance of an aircraft tire on the same soil. This simple method would allow the evaluation of an airfield by measuring the rut depth of a military vehicle, and relating that value to the flotation capacity of the field for a specific aircraft through the use of a previously developed empirical correlation. This type of approach to flotation analysis does not allow a fundamental look at the soil, but it does give a simpl quick method of evaluating airfields without the use of sophisticated equipmen and analysis techniques. Another advantage of this method is that it will allo an absolute evaluation of flotation without waiting for a more fundamental solution to the problem to be developed.

SECTION III

REMOTE SOIL SENSING TECHNIQUES

Remote sensing is not a new science and is highly sophisticated in many specific applications related to problems in agriculture, highway engineering, and military reconnaissance, and consequently a considerable body of knowledge concerning remote sensors has been compiled. The major problem with all remote sensing techniques is that a generalized method of analysis of remote sensor data is not presently possible, and therefore each application/analysis must be related to a set of specific conditions involving the specific sensor, weather, time of year, time of month, and time of day, to mention only a very few of the controlling variables. Thus the conclusions that are reached during some remote sensing application are only applicable to the same original set of conditions, and are not generally applicable. In light of this, a general analysis of remote sensors for application to aircraft flotation/soil surface interaction parameters is not possible, and only a few investigators[1, 2, 3, 4] have studied the specific parameters associated with the military aircraft flotation and operation on soil through the use of remote sensors. Therefore the discussion of remote sensors in this report will include only limited basic descriptions of the remote sensing methods and their possible application to the sensing of flotation parameters.

1. Method Identification

From the diverse selection of remote sensing methods and sensors, eight categories of sensor techniques were selected to be discussed and discussion is limited to specific applications that are directly related to flotation parameters. The eight categories selected are:

Aerial Photography
Infrared
Radar
Laser Profile Recorders

Impact Penetrometers

Microwave Radiometer

Gamma Ray

Multisensor

Limited descriptions, discussions, and references for these categories are provided in Appendix C, and in addition there are a few prime sources for background and detailed descriptions of these categories in the reference list[1, 2, 3, 4, 5, 6]. The Proceedings of the Symposiums on Remote Sensing of Environment, which were held at Michigan University, Ann Arbor, Michigan, are also good sources of remote sensor information.

2. Organizational Review - Remote Sensing Results

Ratings of remote sensing techniques by organizations contacted are provided in Table 2. Again, the comments were somewhat repetitive and they are presented here in condensed form.

Airphoto:

Gives broad area coverage

Is most advanced of all methods of remote sensing

Is not a real time method

Sun angle and other atmospheric conditions are important

Needs expert interpretation

Radar:

Penetrates soil and consequently relates soil properties with depth

Defines only gross topographical features

Moderate to high moisture content will mask soil properties

Is not a real time method

Laser:

Is a rapid real time device

Gives accurate microrelief

Gives a continuous profile

Table 2. Organizational Review and Rating of Remote Sensing Techniques.

Method \ Response No.	1	2	3	4	5	6	7	8	9	10	11	12	Weighted Average
AIRPHOTO	5				1	3	1	3	2			1	2.3
RADAR	7				5	5	5	3	4				4.8
LASER PROFILER	2		2		3	6	7	1					3.5
MULTI-SPECTRAL ANALYSIS	5				2		1						2.7
AERIAL IMPACT PENETROMETER	1		3		4	2	2	2	1				2.1
INFRARED	5					4	4	2				2	3.4
MICROWAVE	4				5		3	4	3				3.8
GAMMA RAY	5				5		6	4					5.0

RATING KEY: Methods are rated in the order of preference (i.e., 1-best, 2-next best, ... 9-least acceptable). Blank blocks indicate that no rating was given in the response.

Does not penetrate foliage to sense soil surface

Needs further development

Needs better altitude reference

Multispectral:

Gives optimum amount of information

Gives good spectral signatures

Is not a real time device

Needs expert analysis

Impact Penetrometer:

Presently gives no correlation to aircraft flotation

Needs many tests for proper evaluation

Strength value has low reliability

Infrared:

Gives good data related to moisture content

Is not a real time device

Measures only surface properties

Microwave:

Gives data with depth

Sensitive to moisture content and soil type

Needs compensation for atmospheric conditions

Gamma Ray:

Is restricted to low altitude flight

Gives no correlation for strength evaluation

Additional sensing techniques suggested which were not listed on the information request form due to their limited stage of development were:

Polarization (optical):

Yields information on surface structure and porosity but has to be used with multispectral data.

Stokes Parameter Analysis:

Yields information on micro- and macrostructure of soils and must be done multispectrally.

In addition to the information request, a trip was made to Willow Run Laboratories at the University of Michigan. Willow Run Laboratories has held all of the previous symposiums on remote sensing of environment, and are currently pursuing state-of-the-art research in remote sensing. As a result of this trip, the following conclusions were drawn as to the application of remote sensing as applied to flotation analysis:

A. All remote sensing is composed of two things: (1) a statistical analysis of the data, and (2) inference of the meaning of the statistical analysis.

B. Remote sensing is in its beginning stages in many areas.

C. The laser profilometer can measure accurate microrelief if it "sees" the surface.

D. Radar systems probably will not be of a great deal of help to flotation analysis.

E. Microwave analysis can be related to moisture content and soil type.

F. An analysis of the technique of a multisensor system has not been done.

G. No one has attempted to study roughness and strength, as related to aircraft flotation and surface operation; therefore, there is no correlation at present between remote devices and parameters used for flotation analysis.

3. Results

In considering the value of the remote sensor as a device for evaluating flotation parameters, it must be remembered that remote sensors (except for the aerial penetrometer) measure an effect rather than some fundamental property of soil. Therefore, parameters such as soil type, moisture content, density, and especially soil strength can only be inferred from the remote sensor data. Additionally, remote sensing analysis results have not been correlated with aircraft flotation and surface operation parameters to the needed degree of accuracy.

In order to discuss the merits of remote sensor devices, the basis of comparison will assume that some measure of strength combined with some measure of microrelief or roughness is necessary to adequately define surface parameters which can be related to aircraft operation capability and that the remote sensor parameters be obtained in real time. Based on the literature review, organizational review, and other factors, the laser profilometer appears to be at present the best sensor method for establishing surface roughness measurements on a real time basis. This method is not as yet operational, but has been shown to accurately measure microrelief to high accuracies[1]. The operation of a laser profilometer is very complicated due to the sophisticated electronics and associated mechanical problems (i.e., aircraft roll and pitch). The data analysis is difficult, since reflections will occur off bushes, grass, trees, etc., and therefore there is doubt as to whether the laser measures the elevation of the soil surface or the top of other vegetation or the surface water over a soil. Due to this feature the laser profiler cannot be used by itself, but rather must be used with a system that accurately tracks the laser beam and describes what surface the laser is sensing.

It appears that the best system for surface roughness evaluation to fit these requirements is a combination of the laser profilometer, infrared scanner, and strip photography[7]. The infrared scanner will accurately plot the path of the laser beam, and the photography will show exactly what has been profiled and with considerable research it should be possible to use such a combined system on a real time basis.

Other remote sensing devices are even more difficult to evaluate since they were not developed for sensing soil surface parameters related to aircraft operation capability. It is very clearly pointed out by Rib[6] that generalizations made from the specific application of one sensor to another application of the same sensor will in all likelihood be wrong. Rib[6] does provide a good compilation of previous remote sensor applications.

At present the best remote sensor method for evaluating soil strength is probably the aerial impact type penetrometer. While this device has not been shown to measure a unique soil strength parameter for different soils, it does measure a soil response that can distinguish between different soil types[8] and provides an estimate of soil strength[9] in specific cases. A similar instrument, which was actually a forerunner to the impact penetrometer, is the aerial cone penetrometer. The aerial penetrometer is also not an accurate soil strength measuring device, but does bracket the value of the soil strength within certain limits.

The aerial impact penetrometer, at present, provides the only remote soil strength measuring technique available on a real time basis, although there is the possibility of inferring both soil strength and surface roughness from other remote sensor devices. Airphoto analysis is probably in a general sense the most advanced remote sensing method and can be used to interpret the type of soil, moisture content, soil strength, and soil surface roughness[4], but presently only after extensive correlation to ground truth data, and with a lower order of accuracy than required. Airphoto analysis is therefore not a real time method and the problems associated with its use and data interpretation are highly sophisticated. Other methods of remote sensing, at this stage, can only provide supplementary information for obtaining soil strength and surface roughness parameters.

SECTION IV

SOIL AND SITE PARAMETERS

Experimental investigations by NASA[10, 11, 12] and others[13, 14, 15, 16] have shown that significant ground loads are induced in aircraft operating on rough runways. These roughness-induced ground loads lead to structural fatigue failures in the aircraft and, in some instances, landing gear failures. The specification of roughness alone for aircraft operating on unprepared runways is not sufficient, however, for estimating ground loads since the stiffness (strength) of the soil tends to reduce the developed ground loads below that which would be encountered on a rigid surface with the same roughness[17]. In fact, for aircraft operations on extremely low strength soil (instantaneous sinkages greater than approximately 4"), little effect of short wavelength ground roughness would be "felt" by the landing gear. Thus, it is evident that a dual parameter system is necessary in order to define the suitability of a site for aircraft operations. A suitable measure of soil strength defines one required parameter, while a suitable measure of surface roughness defines the other required parameter.

1. Soil Parameter (Strength)

Three methods of all those reviewed were considered applicable for defining the required soil strength parameter.

A. A cone penetrometer index

B. California Bearing Ratio (CBR)

C. Military vehicle rut depth correlation.

The first two methods have long been used for defining strength parameters for flotation analysis[18, 19, 20, 21]. The military vehicle rut depth correlation has not been fully investigated, but it does afford the possibility of a simple and quick evaluation method for an empirical airfield strength parameter. Because the third method is not operational at the present time and due to the fact that the cone penetrometer is a better field evaluation tool than the CBR, the cone penetrometer type of index is considered the most suitable means to measure airfield soil strength. The limitations and accuracy associated with the use of the penetrometer certainly suggests the need of a more accurate field evaluation tool. Until such a device is developed through an operational stage which measures more fundamental soil properties, however, the use of the cone penetrometer adequately fulfills the interim requirements. There are four types of cone penetrometers currently available, including the mobility cone, airfield cone, aerial cone, and many variations of the impact cone. Of these four devices the mobility and airfield cone penetrometer are considered most suitable and have been utilized in automated field environment analyzers. Both the mobility and airfield penetrometer provide well-developed correlations between soil strength and aircraft flotation analysis. Also, accurate correlations have been established between these two penetrometers and CBR related flotation data.

2. Site Parameter (Roughness)

Of particular interest in defining surface roughness of soil runways is the determination of surface elevation differences to within approximately one-quarter to one-half inch. Presently used methods of remote sensing of surface elevations were described in Section III. To date, only the laser technique has shown sufficient promise of fulfilling aircraft remote roughness measuring requirements. This section is concerned with the interpretation of roughness data leading to the definition of a roughness parameter. The problem, simply stated, is to define roughness in a precise and meaningful manner with a minimum number of variables.

Interpretation of surface roughness using runway profile data can be based on either a discrete (deterministic) approach[13, 14, 15, 19, 22, 23] or a statistical approach[24, 25, 26, 27, 28]. A summary of each of these approaches is given below.

A. Discrete Method

The basis of most discrete methods is to take either the actual runway profile or a simulated worst condition bump or dip profile and use this profile as input to a mass-spring-damping mathematical model. This model is intended to simulate the actual aircraft through selection of the proper model parameters. Present technology permits an accurate characterization of the aircraft by use of multi-degree of freedom models[13, 14, 19, 23]. The advantages of this approach include the ability to generate greater amounts of and more exact information including the determination of the magnitude and location (on the runway profile) of peak ground induced loads at different stations within the aircraft. The disadvantages include much greater computer running times in comparison to statistical approaches when accurate simulation models are used. Additionally the discrete method does not permit the development of guidelines or limiting values which might be applicable to a broad class of unsurfaced runways.

B. Statistical Methods

The major efforts for ground roughness analysis have been directed at the statistical analysis approach. This effort was partly brought about by the lack of success in early attempts to determine representative bump shapes, amplitudes, and vehicle speed to use in conjunction with landing gear design and also by the previously mentioned large computational times. Two of these statistical approaches are described below.

Power Spectral Density Approach

The power spectral density (PSD) method is a mathematical method of presenting the essential aspects of the profile by showing the distribution of roughness (amplitude as defined by power spectra) with wavelength. The higher the power spectral density at any wavelength, the greater the amplitude or displacement from the mean (roughness). Since the power spectral method represents the average roughness over the length of the runway for various wavelengths, the method cannot identify the magnitude or location of the peak ground induced load. It does, however, permit the quantitative interpretation of levels of roughness.

Using power spectral analysis methods, it has been observed[24, 26] that most man-made surfaces (runways and highways) and natural (virgin) surfaces can be categorized by the simple expression,

$$P(\Omega) = C\Omega^{-N} \qquad (1)$$

where

$P(\Omega)$ = power spectral density of the surface profile height (L^3/cycle/L)

Ω = spatial frequency (cycles/L)

C, N = constants

The value of N has been shown to be approximately 2.0 for natural surfaces[26]. Air Force Flight Dynamics Laboratory has conducted soil runway profile measurements[28] and a curve fit to the bare soil suggested roughness criteria yields an N value of approximately 2.0. If the relationship as given by Equation 1 is valid, then the magnitude of the parameter C provides a measure of surface roughness in a statistical sense. The larger the value of C, the rougher the ground profile.

An alternate parameter to express roughness is to determine the variance (σ) which is the integral on frequency of the power spectral density (Equation 1). This variance is a measure of the deviation (amplitude) of the surface profile from the mean.

Another form of roughness parameter based on the PSD approach was suggested by IITRI[13] and is based on a review of all runway power spectral density plots for paved runways which were available as of 1963. The following single parameter was used as a measure of roughness:

$$Q = \frac{N + D}{2} \qquad (2)$$

where

N = an index related to the horizontal position of the PSD curve at a spectral density of 1.0 in^2/radian/ft.

D = an index related to the vertical position of the PSD curve at a frequency of 2π radians/ft.

The larger the value of Q, the more severe the roughness in relation to landing gear ground loads. Although the power spectral density approach has received considerable use for defining the roughness of paved and unprepared airfields, considerable work remains to be accomplished in correlating PSD with aircraft performance on soil runways particularly through the incorporation of soil strength as it influences roughness.

Vector Approach

Since in specifying roughness the amplitude, wavelength, and repetition must be considered, a vector quantity rather than a scalar quantity has been suggested as a more suitable specification of roughness[29, 30, 31]. This vector method consists of subdividing the plan area to be investigated into a finite number of triangular areas. Each triangular area is assigned a vector (both magnitude and direction). Smooth surfaces have high vector magnitudes and rough surfaces low vector magnitudes. By comparing the orientation (direction) of the vectors in adjacent triangular areas, an indication of roughness can be determined since smooth areas will have low vector dispersions (see Figure 1), while rough areas will have high vector dispersions (see Figure 1).

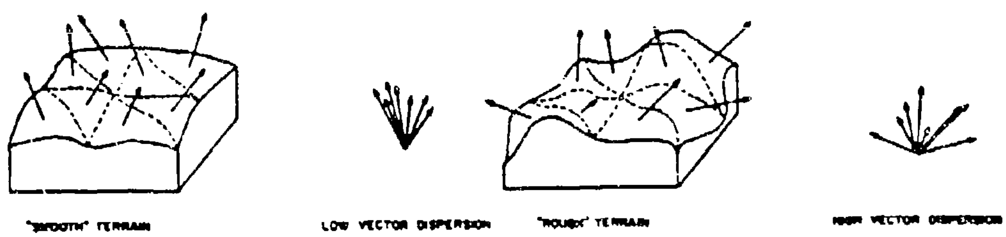

Figure 1. Expression of Roughness

A quantitative description of dispersion (roughness) has been proposed by Fisher[31] as,

$$K = \frac{N - 1}{N - RI} \qquad (3)$$

For smooth surfaces RI approaches N, and K approaches infinity. For rough surfaces, RI approaches zero and K approaches one. This method has been found to be suitable for describing roughness in a general sense[29] but no correlation has been developed to define its suitability for land mobility or aircraft/soil type problems.

Selection of a Site Parameter

At the present time (1970), sufficient correlations between measured soil surface roughness and landing gear loads have not been made to permit the selection of a parameter which adequately defines roughness for aircraft operation on unprepared runways. It is recommended, however, that the roughness parameter C as defined in Equation 1 be used on a preliminary basis as a parameter for specifying limiting magnitudes of ground roughness.

A simplified look at this roughness problem is shown in Figure 2. For high soil strengths (approaching paved runway conditions), the limiting roughness approaches that of paved runways. For example, Hall[22], Houbolt[24], and the proposed airplane military specifications[32] have specified limiting roughness levels for paved runways which yield a C value from Equation 1 of $C = 1.7$ to 2.1×10^{-5} ft. as shown in Figure 2. For low strength soil runways, the ground roughness could be considerably higher since the compressibility of the soil will smooth the input to the landing gear. The proposed military specifications[32] have specified a roughness level for all bare soil runways which yields a C value of $C = 5.0 \times 10^{-3}$ ft. as shown in Figure 2.

It should be recognized that the suggested roughness parameter does not include the influence of soil strength on roughness. As indicated in Figure 2, considerable research needs to be done for the intermediate conditions between high strength and low strength unprepared runways. Additional efforts should include the further evaluation of the parameter C, perhaps in a modified form, as a suitable specification of limiting runway roughness for

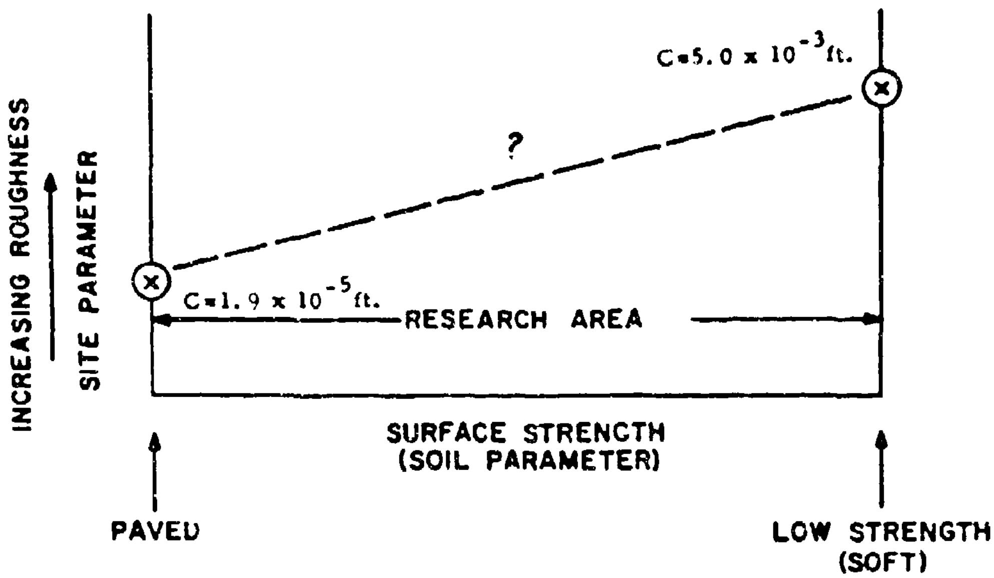

Figure 2. Dual Parameter System

aircraft operations on unprepared runways. Future research on landing gear shock struts, articulated landing gear and active landing gear systems will ultimately influence the magnitude of limiting runway roughness.

SECTION V

APPLICATIONS TO ACTIVE LANDING GEAR SYSTEMS

Current aircraft shock strut landing gears are systems which react to ground induced loads in a passive manner. An active landing gear system is one which permits the programming of the shock strut in anticipation of expected ground roughness. The use of such a programmable shock strut requires the input of surface roughness and ground strength data obtained by remote sensing to the landing gear system. As indicated in Section III, remote sensing devices (radar, infrared, laser, etc.) have been developed through the operational stage only for a limited number of specific applications. The active landing gear system is a totally new proposed use of these remote sensing systems and consequently considerable research and development must be undertaken to bring such a system to the operational stage.

There are two possible modes in which the active landing gear system could be used. For aircraft in landing and take-off operations, the discrete mode would use forward looking remote sensing devices to measure ground strength and roughness in the path of the landing gear system on a real time basis. This data, which provides the input to an onboard computer, would be used to program the landing gear in anticipation of the expected roughness, taking into account the ground deformability based on soil strength. The second, or statistical mode, would utilize airborne remote sensed ground roughness and strength data as a basis for a statistical input for programming the landing gear system in landing and take-off operations. A review of existing techniques of remote sensing of ground roughness and strength for possible application to the active landing gear system is summarized in Table 3 and 4 for the airborne sensing mode and the on-ground sensing mode, respectively. These methods of sensing are defined in terms of their present state of development for application to the active landing gear concept on a real time basis.

Table 3. Aircraft Airborne Sensing (Statistical Mode)

	Research Stage	Feasibility Stage	Operational Stage
Roughness Sensing (Site Parameter)	Airphoto Multisensor	Laser	None
Strength Sensing (Site Parameter)	Airphoto	Air Droppable Penetrometer Military Vehicle Rut Depth*	Cone Penetrometer* Tractor Crawler Penetrometer

* Requires ground crew

Table 4. Aircraft On Ground Forward Sensing (Discrete Mode)

	Research Stage	Feasibility Stage	Operational Stage
Roughness Sensing (Site Parameter)	Laser	None	None
Strength Sensing (Site Parameter)	Microwave**	None	None

** Suggested as holding research promise[33]

As indicated in Table 4 the aircraft airborne (statistical) mode is in the most advanced state of development for application to the active landing gear. Recent work by the U. S. Army Tank-Automotive Command[33] have shown the potential for using active suspension systems in reducing ground induced loads. Although the use of airborne sensors and on-ground remote sensors in conjunction with a programmable landing gear holds promise for potential reductions in landing gear loads in landing and take-off operations, considerable research and development still remains to be accomplished.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. The results of the literature review, the organizational review, and this study indicate that:

A. The cone penetrometer is the only operational device for evaluating an adequate measure of soil strength for rapid in situ procedures which satisfy the requirements of portable equipment, rapid measurement, and little or no data reduction. The mobility and airfield cone penetrometer presently fulfill these requirements, and the military vehicle rut depth correlation technique is also very promising.

B. The aerial impact penetrometer and the tractor crawler penetrometer (automated field station) are the only devices which have been shown to be feasible for evaluating a measure of soil strength by remote techniques although a microwave device has been suggested as having potential for soil strength evaluation. Aerial photographs can be used to infer soil strength with limited accuracy but at the present time (1970) cannot provide this information on a real time basis.

C. The laser profilometer is the only device which appears feasible for determining an adequate measure of ground roughness on a real time basis, but it appears that the laser device will have to utilize other remote sensors (infrared and photographic) in order to become an operational technique.

2. On this basis, then:

A. Research efforts should be continued on correlating cone penetrometer indices (both AI and CI) with aircraft operations flotation performance on unprepared runways, utilizing the cone penetrometer indices as the only soil strength parameter until such time as future research indicates a better in situ rapid evaluation technique. In addition, research efforts should be undertaken to fully evaluate the military vehicle rut depth correlation technique through a limited number of field operations. Such a technique can provide a vital interim tool immediately usable to pilots for determining the suitability of sites for aircraft operations.

B. A suitable method of expressing surface roughness (the site parameter) has not been developed to date. Although several roughness parameters have been suggested, none have been fully verified through correlations of aircraft performance on soil runways. On a preliminary basis the roughness parameter, C, would be used as a site parameter. Considerable research remains to be accomplished in determining a suitable method for expressing roughness which, when combined with the soil parameter, will permit the determination of the operational capacity of aircraft on unprepared runways.

C. Should research efforts leading to the development of the active landing gear system continue, then research should also continue primarily on the laser profilometer device but also on the other remote sensors as research shows the feasibility of these sensors to active landing gear applications. A description of the state-of-the-art (1969) of all remote sensors and their applications can be found in Needleman's report[34].

REFERENCES

1. Buckmeier, F. J., et al.; Airborne Remote-Sensing Techniques for Site Selection: AFWL-TR-65-115, AD845756, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, December, 1968.

2. Forrest, R. B.; Site Selection Techniques: AFWL-TR-67-146, AD835230, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, May, 1968.

3. Brody, R. H., et al.; Engineer Route Reconnaissance Feasibility Study: Contract No. DA44009-AMC-1231(X), AD828489, U.S. Army Engineer Gimrada, Ft. Belvoir, Virginia, March, 1967.

4. Shamburger, J. H.; Mobility Environmental Research Study, A Quantitative Method for Describing Terrain for Ground Mobility: AD835392, U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, May, 1968.

5. Remote Sensing and its Application to Highway Engineering: Highway Research Board Special Report #102, Publication 1640, H.R.B. Division of Engr. National Research Council, Washington, D. C., 1969.

6. Rib, H. T.; An Optimum Multisensor Approach for Detailed Engineering Soils Mapping, Vol. I: Joint Highway Research Project C-36-32U, PB-176310, Purdue University, Lafayette, Indiana, December, 1966.

7. Letter of Communication with Air Force Weapons Lab, Kirtland Air Force Base, New Mexico.

8. Schmid, W. E.: The Determination of Soil Properties In-Situ by An Impact Penetrometer: AFCRL66-43, Princeton University, Princeton, New Jersey, January, 1966.

9. Tsai, Kuei-wu; Strength Response Parameters of Natural Soil Surfaces and Their Application to the Landing Problem of Aircraft: Project No. 7628, AFCRL67-0583, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, January 19, 1966 through January 18, 1967.

10. Morris, Garland J., and Stickle, Joseph W.; Response of a Light Airplane to Roughness of Unpaved Runways: Technical Note D-510, National Aeronautics and Space Administration, Washington, D. C., September, 1960.

11. Turner, Frank; Analysis of Criteria for Pavement Slopes: SRDS RD-65-53, AD650842, Midwest Research Institute, Kansas City, Missouri, May, 1965.

12. Morris, Garland J.; Response of Several Turbojet Airplanes to Runway Roughness: NASA TN D-5740, National Aeronautics and Space Administration, Washington, D.C., March, 1970.

13. Hahn, Edward E.; Design Criteria for Ground-Induced Dynamic Loads: RTD-TDR-63-4139 - Vol. 1, AD600923, Air Force Flight Dynamics Laboratory, WPAFB, Ohio, November, 1963.

14. Neugent, Jack; Location of Rough Areas of Runways for B-52 Aircraft, Volume I through IV, AFFDL-TR-67-175, Air Force Flight Dynamics Laboratory, W-PAFB, Ohio, March, 1968.

15. Green, Andrew J., and Rush, Edgar S.; Pilot Study of Response of CV-2 Aircraft to Irregular Terrain: Technical Report No. 3-790, AD 818980, Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, July, 1967.

16. Richmond, L. D., et al.; Aircraft Dynamic Loads from Substandard Landing Sites Parts 1 through 4: AFFDL-TR-67-145, Air Force Flight Dynamics Laboratory, W-PAFB, Ohio, September, 1968.

17. Womack, L. M.; Tests With a C-130E Aircraft on Unsurfaced Soils: Misc. Paper MP-4-712, U. S. Army Waterways Experiment Station, Vicksburg, Mississippi, February, 1965.

18. Kraft, D. C., Luming, H., and Hoppenjans, J. R.; Aircraft Landing Gear - Soils Interaction and Flotation Criteria, Phase II: AFFDL-TR-69-76, Air Force Flight Dynamics Lab, WPAFB, Ohio, November, 1969.

19. Crenshaw, B. M., W. B. Truesdale, and C. K. Butterworth; Aircraft Landing Gear Dynamic Loads from Operation on Clay and Sandy Soil: Technical Report AFFDL-TR-69-, Air Force Flight Dynamics Laboratory, WPAFB, Ohio, March, 1969.

20. Hendrickson, Clendon L., and Joe Schiele; Project Rough Road Alpha, Take-Off and Landing Capabilities of C-13B, JC-130B, NC-130B (BLC), C-123B, and YC-123H Aircraft On Off-Runway (Unprepared) Surfaces: FTC-TDR-63-8, AD407144, Air Force Flight Test Center, Edward Air Force Base, California, April, 1963.

21. Needleman, Stanley M., Donald W. Klick, and Carlton E. Molineux; Evaluation of an Arctic Ice-Free Land Site and Results of C-130 Aircraft Test Landings, Polaris Promontory, North Greenland, 1958-1959: AFCRL252, AD260228, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, March, 1961.

22. Hall, Albert W., and Sheldon Kopelson; The Location and Simulated Repair of Rough areas of a Given Runway by an Analytical Method: Technical Note D-1486, National Aeronautics and Space Administration, Washington, D. C., October, 1962.

23. Wignot, J. E., et al.; The Development of Dynamic Taxi Design Procedures, Report No. FAA DS 68-11, AD673424, Lockheed California Co., Burbank, California, June, 1968.

24. Houbolt, John C., Walls, James H., and Smiley, Robert F.; On Spectral Analysis of Runway Roughness and Loads Developed During Taxiing: Technical Note 3484, National Advisory Committee for Aeronautics, Washington, D. C., July, 1955.

25. Thompson, Wilbur E.; Measurements and Power Spectra of Runway Roughness at Airports in Countries of the North Atlantic Treaty Organization: Technical Note 4303, National Advisory Committee for Aeronautics, Washington, D. C., July, 1958.

26. Van Deusen, B. D.; A Statistical Technique for the Dynamic Analysis of Vehicles Traversing Rough Yielding and Non-Yielding Surfaces: NASA CR-659, Washington, D. C., March, 1967.

27. Van Deusen, B. D., Sneyd, J. M., Hoppe, C. H., and Hughes, R. F.; Experimental Verification of Surface Vehicle Dynamics: NASA CR-1399, Washington, D. C., September, 1969.

28. Groomes, B. H.; Sod and Matted Landing Surface Roughness Characteristics, FDDS-TM-64-32, AD617544, Air Force Flight Dynamics Laboratory, W-PAFB, Ohio, December, 1964.

29. Stone, R. O., and Dugundji, J.; "A Study of Microrelief - Its Mapping, Classification, and Quantification by Means of a Fourier Series:" Engineering Geology, 1(2), 1965.

30. Turner, A. K., and Miles, R. D.; "Terrain Analysis by Computer:" Proceedings of the Indiana Academy of Science for 1967, Volume 77, 1968.

31. Fisher, R. A.; Dispersion on A Sphere: Proceeding Royal Society of London, Series A. 217, 1953.

32. Proposed Military Specification - Airplane Strength and Rigidity, Landplane Landing and Ground Handling Loads, Mil-A-8862A, prepared by Air Force, July, 1969.

33. Cameron, John W.; High Cross-Country Speed: First International Conference on Vehicle Mechanics, Wayne State University, Detroit, Michigan, July, 1968.

34. Needleman, S. M.; Earth Science Applied to Military Use of Natural Terrain: AFCRL-69-0364, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, August, 1969.

APPENDIX A

Bibliography

The list of literature that appears in this Appendix has been crossed referenced in relation to both remote and in situ flotation parameter evaluation methods. Some of the articles listed have no cross indexing, as these articles are not directly related to any specific evaluation method. The following key to this Appendix defines the reference symbols.

KEY TO CROSS REFERENCING SYMBOLS

Symbol	
	In Situ Methods
1	Mobility Cone Penetrometer
2	Airfield Cone Penetrometer
3	Remolding Index
4	Rating Cone Index
5	Nuclear Devices
6	California Bearing Ratio
7	Bevameter Bearing and Shear Devices
8	Sheargraph
9	Dimensional Analysis (Military Vehicle To Aircraft Flotation Capacity)
10	Related Topics
	Remote Methods
A	Airphoto
B	Infrared
C	Radar
D	Laser
E	Impact Penetrometers
F	Other Regions of the Electro-Magnetic Spectrum
G	Related Topics
R	Roughness

CROSS
INDEX

A — Albareda, J. M., F. Monturiol, A. Guerra, and E. F. Galiano: Study of the Physical Properties of Soils Through Interpretation of Aerial Photographs: Contract No. DA-91-591-EUC-3285, AD464817, Instituto De Edafologia Y Fisiologia Vegetal, Serrano, 113 - Madrid (6) - Spain, 1st April, 1964 to 31st March, 1965.

A — Artsybashev, Ye. S.; "Study of the Spectral Brightness of Some Landscape Elements for Interpretation of Ground Water on Aerial Photographs": AD692647, Akad Nauk SSSR. Laboratoriia Aerometodov, Primeachie Aero-metodov, Siia Izucheniia, Gruntouyhk, Vod., pp. 90-123, 1962, U.S.S.R., FSTC-HT-23-353-68, Army Foreign Science and Technology Center, Washington, D. C., June, 1969.

A — Avery, Thomas E.; Interpretation of Aerial Photographs: Burgess Pub. Co., Minneapolis, Minnesota, 1962.

1, 3, 4 — Bassett, J. R., A. R. McDaniel, and S. J. Knight: Variation in Trafficability of Four Loess Soils: Miscellaneous Paper No. 4-838, AD-800144, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, August, 1966.

E — Blackmon, C. A., et al.; Studies of Aerial Cone Penetrometer, Field Tests in Fine-Grained Soils, 1960: Technical Report No. 3-462, Report 3, AD450613, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, August, 1963.

A, D — Brody, R. H., et al.; Engineer Route Teconnaissance Feasibility Study: Contract No. DA-44009-AMC-1231, AD828489, U.S. Army Engineer Gimrada, Ft. Belvoir, Virginia, March, 1967.

C — Brown, Walter E., Jr.; "Radar Studies of the Earth": Proceedings of the IEEEE: Vol. 57, No. 4, April, 1969.

A, B, C, D, E, F — Buckmeier, F. J., et al.; Airborne Remote-Sensing Techniques for Site Selection: AFWL-TR-65-115, AD845756, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, December, 1968.

CROSS
INDEX

G — Cameron, John W.; High Cross-Country Speed: First International Conference on Vehicle Mechanics, Wayne State University, Detroit, Michigan, July, 1968.

8 — Cohron, Gerald T., "Soil Sheargraph." Agricultural Engineering: October, 1963.

8 — Cohron, G. T.; "Cohron Sheargraph for Shearing Strength Measurements," Journal of Environmental Science: December, 1963.

G — Colwell, R. N.; "Uses and Limitations of Multispectral Remote Sensing," Proceedings of the Fourth Symposium on Remote Sensing of Environment: AD638-919, The University of Michigan, Ann Arbor, Michigan, April, 1966.

1, 2, 6, 7 — Crenshaw, B. M., W. B. Truesdale, and C. K. Butterworth; Aircraft Landing Gear Dynamic Loads From Operation on Clay and Sandy Soil: Technical Report AFFDL-TR-69, Air Force Flight Dynamics Laboratory, WPAFB, Ohio, March, 1969.

B — Davis, B. R., E. B. Lipscomb, and S. J. Knight; Terrain Analysis by Electromagnetic Means, Report 1, Laboratory Investigations in the 0.76- to 5.00-Micron Spectral Region: Technical Report No. 3-693, AD-472873, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, October, 1965.

F — Edgerton, A. T.; "Engineering Applications to Microwave Radiometry," Proceedings of the Fifth Symposium on Remote Sensing of Environment: AD676327, The University of Michigan, Ann Arbor, Michigan, April, 1968.

G — Ellermeier, R. D.; Project Themis: A Center for Remote Sensing: AD683584, Advanced Research Projects Agency, Department of Defense, Work Order 1079, October, 1968.

2 — Fenwick, W. B.; Description and Application of Airfield Cone Penetrometer: AD-800746, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, October, 1965.

Fisher, R. A.; Dispersion on a Sphere: Proceeding Royal Society of London, Series A. 217, 1953.

CROSS
INDEX

A, B, C — Forrest, R. B.; Site Selection Techniques: AFWL-TR-67-146, AD835230, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, May, 1968.

1 — Freitag, D. R.; Penetration Tests for Soil Measurements: Miscellaneous Paper No. 4-960, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, January, 1968.

A — Galkina, Ye. A.; "Swampy Forest Zone Terrain," Geographical Reference Book: AD692654, Vol. 7, pp. 75-84, 1955, FSTC-HT-23-736-69, Army Foreign Science and Technology Center, Washington, D. C., August, 1969.

1, 3, 4, 7, 8 — Grabau, Warren E.; A Suggested Procedure for the Selection and Description of Reference Test Areas: Miscellaneous Paper No. 4-921, AD658659, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, August, 1967.

6 — Gravenhorst, E. G.; A Study on Feasibility and Method of Improving Flotation for Moving Types A2F, A4D, F4D, F4H, F8U-1, and F8U-2, Aircraft over Unprepared Expeditionary Airfields: AD295172, Arkwin Industries, Inc., Westbury, New York, November 2, 1962.

6 — Gray, Donald H., and Donald E. Williams; Evaluation of Aircraft Landing Gear Ground Flotation Characteristics For Operation From Unsurfaced Soil Airfields: Technical Report ASD-TR-68-34, WPAFB, Ohio, September, 1968.

R — Green, Andrew J., and Rush, Edgar S.; Pilot Study of Response of CV-2 Aircraft to Irregular Terrain: Technical Report No. 3-790, AD818980, Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, July, 1967.

10, G — Grenke, W. C.; Observing, Analyzing, and Forecasting the State of the Ground: Report No. 3-112, AD-616616, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, May, 1965.

R — Groomes, B. H.; Sod and Matted Landing Surface Roughness Characteristics: FDDS-TM-64-32, AD617544, Air Force Flight Dynamics Laboratory, WPAFB, Ohio, December, 1964.

CROSS INDEX

R — Hahn, Edward E.: Design Criteria for Ground - Induced Dynamic Loads: RTD-TDR-63-4139 - Vol. I, AD600923, Air Force Flight Dynamics Laboratory, WPAFB, Ohio, November, 1963.

R — Hall, Albert W., and Sheldon Kopelson: The Location and Simulated Repair of Rough Areas of a Given Runway by an Analytical Method: Technical Note D-1486, National Advisory Committee for Aeronautics, Washington, D.C., October, 1962.

1, 2, 6, 9 — Hammitt, G. M., II; Evaluation of Soil Strength of Unsurfaced Forward Airfields by Use of Ground Vehicles: U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, May, 1968.

2, 6 — Hendrickson, Clendon L., and Joe Schiele; Project Rough Road Alpha, Take-Off and Landing Capabilities of C-13B, JC-130B, NC-130B (BLC), C-123B, and YC-123H Aircraft On Off-Runway (Unprepared) Surfaces: FTC-TDR-63-8, AD4071444, Air Force Flight Test Center, Edward Air Force Base, California, April, 1963.

R — Houbolt, John C., Walls, James H., and Smiley, Robert F.; On Spectral Analysis of Runway Roughness and Loads Developed During Taxiing: Technical Note 3484, National Advisory Committee for Aeronautics, Washington, D.C., July, 1955.

2, 6 — Johnson, Raymond L., Clendon L. Hendrickson, Joe S. Schiele, and William R. Loewe; An Evaluation of C-130B Short Field Take-Off and Landing Capabilities on Unprepared Surfaces: TD No. 62-25, FTC-TDR-62-25, AD-294566, Edwards Air Force Base, California, August, 1962.

F — Kennedy, J. M., and R. T. Sakamoto; "Passive Microwave Determinations of Snow Wetness Factors," Proceedings of the Fourth Symposium on Remote Sensing of Environment: The University of Michigan, Ann Arbor, Michigan, April, 1966.

10, G — Kennedy, J. G., and T. E. Hicks; Trafficability Predictions in Tropical Soils: Miscellaneous Paper No. 4-355, AD-845616, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, November, 1968.

CROSS INDEX

10, G — Knight, S. J.; Trafficability of Soils - A Summary of Trafficability Studies Through 1955: Technical Memorandum No. 3-240, AD121975, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, December, 1956.

10 — Kraft, D. C., Luming, H., and Hoppenjans, J. R.; Aircraft Landing Gear - Soils Interaction and Flotation Criteria, Phase II: AFFDL-TR-69-76, Air Force Flight Dynamics Lab, WPAFB, Ohio, November, 1969.

10, G — Lassaline, David M., and William L. Harrison, Jr.; The Prediction of Soil Strength Parameters in Remote or Inaccessible Areas by Means of Soil Analogs: Technical Report No. 8816-(LL102), AD-465409, U.S. Army Tank Automotive Center, Warren, Michigan, April, 1965.

B — Lavecchia, N. J., Jr., A. N. Williamson, Fr., and H. J. Nikodem; Terrain Analysis by Electromagnetic Means, Report 4, Laboratory Investigations of the Infrared Emissivity of Soils Below a Wavelength of 7.7 Microns: Technical Report No. 3-693, AD815453, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, May, 1967.

S — LeFebre, E. W., and P. G. Manke; A Preliminary Standardization and Calibration Procedure for Nuclear Depth Moisture/Density Gages: PB-175950, Oklahoma State University, Stillwater, Oklahoma, May, 1967.

G — Leighty, R. D.; "Remote Sensing for Engineering Investigation of Terrain (Introduction)," Proceedings of the Fifth Symposium on Remote Sensing of Environment: AD676327, The University of Michigan, Ann Arbor, Michigan, April, 1968.

C — Leighty, R. D.; "Remote Sensing for Engineering Investigation of Terrain - Radar Systems," Proceedings of the Fifth Symposium on Remote Sensing of Environment, AD676327, The University of Michigan, Ann Arbor, Michigan, April, 1968.

D — Link, L. E.; "Capability of Airborne Laser Profilometer to Measure Terrain Roughness," Sixth Symposium on Remote Sensing of Environment: University of Michigan, Ann Arbor, Michigan, October 13-16, 1969. (Abstract)

CROSS
INDEX

D — Link, L. E.; Capability of Airborne Laser Profilometer to Measure Terrain Roughness: U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

B, C, F — Lipscomb, Ernest B.; Terrain Reconnaissance with Electromagnetic Sensors: Miscellaneous Paper No. 4-630, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, February, 1964.

1, 7 — Liston, R. A., T. Csako, P. Haley, W. L. Harrison, Jr., B. Hanamoto, and L. Martin: Mobility Environmental Research Study Mobility Testing Procedures: AD-800462, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, February, 1966.

A — Lueder, Donald R.; Aerial Photographic Interpretation: Principles and Applications: New York, McGraw-Hill, 1959.

1, 3, 4 — McDaniel, A. R.; Trafficability Predictions in Tropical Soils: Report 3, Miscellaneous Paper No. 4-355, AD-801321, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, August, 1966.

A — Mintzer, O. W.; "Remote Sensing for Engineering Investigation of Terrain - Photographic Systems," Proceedings of the Fifth Symposium on Remote Sensing of Environment: AD676327, The University of Michigan, Ann Arbor, Michigan, April, 1968.

1 — Molineux, C. E.; Automated Field Station for Monitoring Soil Properties: Air Force Cambridge Research Laboratories, Cambridge, Massachusetts.

E — Molineux, Carlton E.; Remote Determination of Soil Trafficability by the Aerial Penetrometer: AFCRC TN-55-223, AD92254, Air Force Cambridge Research Center, Bedford, Massachusetts, October, 1955.

R — Morris, Garland J., and Stickle, Joseph W.; Response of a Light Airplane to Roughness of Unpaved Runways: Technical Note D-510, National Aeronautics and Space Administration, Washington, D. C., September, 1960.

CROSS INDEX

R Morris, Garland J.; Response of Several Turbojet Airplanes to Runway Roughness: NASA TN D-5740, National Aeronautics and Space Administration, Washington, D.C., March, 1970.

A Mullins, Bill; Factors and Procedures Influencing the Reliability of Agricultural Data From Earth Orbiting Sensor Systems: N68-11810, Systems Technology and Applied Research Corporation, Dallas, Texas, June 27, 1967.

B Murcray, David G., Frank H. Murcray, and Walter J. Williams; Infrared Radiance of Selected Terrain Features as Viewed From High Altitude: AFCRL-67-0448, AD658866, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, July, 1967.

1, 2, 6 Needleman, Stanley M., Donald W. Klick, and Carlton E. Molineux; Evaluation of an Arctic Ice-Free Land Site and Results of C-130 Aircraft Test Landings, Polaris Promontory, North Greenland, 1958-1959: AFCRL252, AD260228, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, March, 1961.

R Neugent, Jack; Location of Rough Areas of Runways for B-52 Aircraft, Volume I through IV: AFFDL-TR-67-175, Air Force Flight Dynamics Laboratory, WPAFB, Ohio, March, 1968.

F Nikodem, H. J.; "Effects of Soil Layering on the Use of VHF Radio Waves for Remote Terrain Analysis," Proceedings of the Fourth Symposium on Remote Sensing of Environment: AD638-919, The University of Michigan, Ann Arbor, Michigan, April, 1966.

B Parker, D. C.; "Remote Sensing for Engineering Investigation of Terrain - Infrared Systems," Proceedings of the Fifth Symposium on Remote Sensing of Environment: AD676327, The University of Michigan, Ann Arbor, Michigan, April, 1968.

A Parry, J. T., W. R. Cowan, and J. A. Heginbottom; Soil Studies Using Color Photos: AD690042, Photogrammetric Engineering, Vol. 35/1:44-56, January, 1969.

CROSS INDEX

A, B, C, D, F — Rib, H. T.; An Optimum Multisensor Approach for Detailed Engineering Soils Mapping, Vol. I: Joint Highway Research Project C-36-32II, PB-176312, Purdue University, Lafayette, Indiana, December, 1966.

2, 6 — Richmond, L. D., K. J. Debord, and J. R. Fuller; Aircraft Dynamic Loads From Substandard Landing Sites: Phase I Interim Technical Report, 06-16199, The Boeing Company, Renton, Washington, November, 1965.

R — Richmond, L. D., et al.; Aircraft Dynamic Loads from Substandard Landing Sites, Parts I through 4: AFFDL-TR-67-145, Air Force Flight Dynamics Laboratory, WPAFB, Ohio, September, 1968.

7 — Reece, Alan R.; Problems of Soil Vehicle Mechanics: Report No. 8470, AD450151, U. S. Army Tank-Automotive Center, Warren, Michigan, March, 1964.

A, B, C, D, F — Remote Sensing and its Application to Highway Engineering: Highway Research Board Special Report #102, Publication 1640, H. R. B. Division of Engr. National Research Council, Washington, D. C., 1969.

D — Remple, Robert, C., and Parker, A. K.; "An Information Note on an Airborne Laser Terrain Profiler and Micro-Relief Studies," Proceedings of the Third Symposium on Remote Sensing of Environment: AD614032, The University of Michigan, Ann Arbor, Michigan, February, 1965.

5 — Rosser, T. B., III, and S. L. Webster; Evaluation of Nuclear Methods of Determining Surface In-Situ Soil Water Content and Density: Miscellaneous Paper S-69-15, AD-688079, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, April, 1969.

1, 3, 4 — Rush, E. S.; Trafficability Tests With the 5-Ton Goer (XM520) on Fine - and Course-Grained Soils: Miscellaneous Paper No. 4-477, AD-646591, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, April, 1962.

A — Sabey, Barbara E., and G. N. Lupton: Measurement of Road Surface Texture Using Photogrammetry: RRL Report LR57, PB176680, Road Research Lab., Crowthorne, England, 1967.

CROSS INDEX	
E	Schmid, W. E.; The Determination of Soil Properties In-Situ by An Impact Penetrometer: AFCRL66-43, Princeton University, Princeton, New Jersey, January, 1966.
1, 2, 4, 8, A	Shamburger, J. H.; Mobility Environmental Research Study, A Quantitative Method for Describing Terrain for Ground Mobility: AD835392, U.S.A. E. W. E. S. Corps of Engineers, Vicksburg, Mississippi, May, 1968.
7	Sloss, D. A., Jr., and D. M. Lassaline; A Study of Tropical Soil Strengths: Presented at the Second International Meeting of the International Society for Terrain-Vehicle Systems, Quebec City, Canada, August, 1966.
10, G	Stone, Richard O., and J. Dugundji; "A Study of Microrelief - Its Mapping, Classification, and Quantification by Means of a Fourier Analysis," Eng. Geol.: Vol. 1, No. 2, pp. 89-187, 1965.
A	TaLiang; Tropical Soils: Characteristics and Airphoto Interpretation: AD613555, prepared for Air Force Cambridge Research Laboratories, Bedford, Massachusetts, August 31, 1964.
1	Terry, Cyrl W., Ph.D.; Investigation of New Instrumentation and Techniques for Rapid Evaluation, of Load Bearing Capacity of Temporary Roads, Runways and Compacted Areas (Snow & Soil): Technical Note N-852, Y-R011-01-01-097, AD684432, U. S. Naval Civil Engineering Laboratory, Port Hueneme, California, October, 1966.
A	Thompson, Will F.; Physical Geography and Military Environment in a Transect of the Utah and Colorado Rockies: Technical Report 69-73-ES, 1T062112A129, AD693244, U.S. Army Natick Laboratories, Natick, Massachusetts, May, 1969.
R	Thompson, Wilbur E.; Measurements and Power Spectra of Runway Roughness at Airports in Countries of the North Atlantic Treaty Organization: Technical Note 4303, National Advisory Committee for Aeronautics, Washington, D. C., March, 1967.
10, E	Tsai, Kuei-wu; Strength Response Parameters of Natural Soil Surfaces and Their Application to the Landing Problem of Aircraft: Project No. 7628, AFCRL67-0583, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, January 19, 1966 through January 18, 1967.

CROSS INDEX

R — Turner, Frank: Analysis of Criteria for Pavement Slopes: SRDS RD-65-53, AD650842, Midwest Research Institute, Kansas City, Missouri, May, 1965.

G — Turner, A. K., and Miles, R. D.: "Terrain Analysis by Computer:" Proceedings of the Indiana Academy of Science for 1967, Volume 77, 1968.

R — Van Deusen, B. D.; A Statistical Technique for the Dynamic Analysis of Vehicles Traversing Rough Yielding and Non-Yielding Surfaces: NASA CR-659, Washington, D. C., March, 1967.

R — Van Deusen, B. D., Sneyd, J. M., Hoppe, C. H., and Hughes R. F.: Experimental Verification of Surface Vehicle Dynamics: NASA CR-1399, Washington, D. C., September, 1969.

B — Vincent, Robert K., and Graham R. Hunt: "Infrared Reflectance from Mat Surfaces," Applied Optics: Vol. 7, No. 7, January, 1968.

6 — Washolder, B. V.; Investigation of Test Bed for Airfield Matting Test Facility Model Soils and Boundary Effects: Naval Air Engineering Lab (Ship Installation), Philadelphia, November, 1965, AD 820420.

6 — Westberg, J. V.; Study of the Effects of Aircraft Landing Gear Parameters on Support Area Airfield Flotation Capability: Report 50088, C30-66-154, Douglas Aircraft Group, Long Beach, California, May, 1965.

6 — Westberg, J. V.; Study of the Effects of Support Area Airfields on the Ground Performance of Heavy Logistics Transport Aircraft: C30-66-154, Report 50089, Douglas Aircraft Company, Inc., Long Beach, California, 1965.

R — Wignot, J. E., et al.; The Development of Dynamic Taxi Design Procedings, Report No. FAADS 68-11, AD673424, Lockheed California Co., Burbank, California, June, 1968.

5 — Williamson, T. G., and Witczak, M. W.: Laboratory and Field Evaluation of the Nuclear Moisture and Density Meters: Joint Highway Research Project C-3616E, PB-169908, Purdue University, Lafayette, Indiana, February, 1966.

CROSS
INDEX

R — Womack, L. M.; Tests With a C-130E Aircraft on Unsurfaced Soils: Misc. Paper MP-4-712, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, February, 1965.

S — Womack, L. M.; Tests With A C-130-E Aircraft on Unsurfaced Soils: Miscellaneous Paper No. 4-712, AD-613170, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, February, 1965.

1, E — Womack, David P., and William R. Cox; Measurement of Dynamic Characteristics of Soils with Penetrometers: NASA-CR-849, by the University of Texas, Austin, Texas, August, 1967.

5 — Yong, R. N., and R. D. Japp; Soil Water Relationships and Their Engineering Applications: AD-686512, McGill University, Montreal, Canada, May 7, 1966.

10, G — A Technique for MacroGeometry Terrain Analysis: AD658655, from Department of Civil Engineering, Vanderbilt Univeriayt, Nashville, Tennessee, 1 March, 1963.

A — A Terrain Brief: M. E. X. E. Test Report No. 931, AD809694, Military Engineering Experimental Establishment, Christchurch, Hampshire, England, November, 1965.

2, 6 — Aircraft Operations on Unsurfaced Soil, Soil Measurements and Analysis Project Rough Road Alpha: Technical Report No. 3-624, AD410099L, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, June, 1963.

B — Dual Channel Airborne Infrared Imaging System: N69-26346, Texas Instruments Inc., Dallas, Texas, March 28, 1969.

2 — Field Environment Analyzer for Safe Aircraft-Bearing Land Evaluation (Feasible): Proposal HP-001, U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, February, 1967.

A — Forecasting Trafficability of Soils, Airphoto Approach: AD409916, Technical Memorandum No. 3-331, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, June, 1963.

CROSS INDEX	
G	Gamma Ray Measurement of Pavement Density and Bridge Research Program: Highway Research Board Special Report #38, Publication 627, H. R. B. Division of Engineering, National Research Council, Washington, D.C., 1958.
A	"Manual of Photographic Interpretation," American Society of Photogrammetry: Washington, D. C.
A	"Manual of Photogrammetry, Vol. I & II." American Society of Photogrammetry: Falls Church, Virginia, 1966.
A	Photographic and Photogrammetric Methods of Terrain Analysis for Determination of Aircraft Landing Sites: AFCRL-62-644, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, June 1962, AD282536.
R	Proposed Military Specification - Airplane Strength and Rigidity, Landplane Landing and Ground Handling Loads: MIL-A-8862A, prepared by Air Force, July, 1969.
7	Research Report No. 6: DA Project 1-V-0-21701-A-045, AD-651-726, Technical Report No. 9560, U.S. Army Tank Automotive Center, Warren, Michigan, November, 1966.
1, 6	Sinkage of a Dual Aircraft Wheel Assembly: Report 925, AD479330, Military Engineering Experiment Station, Christchurch, Hampshire, England, October, 1965.
	Sixth Symposium on Remote Sensing of Environment: October 13, 14, 15, 16, 1969, Abstracts, The University of Michigan, Ann Arbor, Michigan.
1, 3, 4	Soils Trafficability: TB-ENG-37, Headquarters, Department of the Army, Washington 25, D. C., July 10, 1959.
A	Terrain Evaluation Symposium: M. E. X. E. Report No. 1053, AD844413, Military Engineering Experimental Establishment, Christchurch, Hampshire, England, December 6, 1968.

CROSS
INDEX

1, A — Trafficability of Soils: Soil Classification: Technical Memorandum No. 3-240, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, August, 1961.

C — Waterways Experiment Station - Terrain Analysis Radar: AD465-403, Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi, January, 1965.

APPENDIX B

Organizational Review Letter

The following is an exact duplicate of the letter and information request sent to these organizations for review and comment.

Douglas Aircraft Co. Inc.
Long Beach, California

Lockheed-Georgia Co.
Marietta, Georgia

IIT Research Institute
Chicago, Illinois

Waterways Experiment Station
Vicksburg, Mississippi

Princeton University
Princeton, New Jersey

U.S. Army Tank-Automotive Center
Warren, Michigan

Air Force Cambridge
Research Laboratories
Bedford, Mass.

U.S. Naval Civil Engineering
Laboratories
Port Hueneme, California

The Boeing Company
Renton, Washington

Cornell Aeronautical Lab. Inc.
Buffalo New York

Air Force Weapons Lab
Kirtland AFB, New Mexico

Texas Instruments Inc.
Dallas, Texas

Booz-Allen Applied Research, Inc.
Cleveland, Ohio

Boeing Company
Morton, Pennsylvania

General Dynamics
Fort Worth, Texas

Grumman Aircraft
Bethpage, New York

State University of New York
Buffalo, New York

University of Texas
Austin, Texas

Howard University
Washington, D.C.

Old Dominion University
Norfolk, Virginia

UNIVERSITY OF DAYTON
DAYTON, OHIO 45409

RESEARCH INSTITUTE

Dear Mr.

Attached are two copies of the information request we discussed recently. Please keep one copy for your own file and return the other copy to me after completing your review of it.

Thank you for your interest and cooperation.

Sincerely,

Dr. David C. Kraft
Assoc. Professor, Civil Engineering
and Engineering Mechanics
University of Dayton Research Institute

DCK:mw
Encl.

SUBJECT: In-Situ Rapid Testing and Remote Sensing of Soil Properties

1. Your participation is requested in a current University of Dayton program to identify and evaluate current methods of in situ rapid testing and remote sensing of soil properties which will define soil properties applicable to aircraft flotation and operation on soil surfaces. These methods refer to tests and/or measurements common to mobility and flotation type problems.

2. Based on our initial review of existing literature and/or research studies, a listing of existing methods has been prepared and is attached. Your review of the listing and the addition of your applicable comments as well as an indication of the method or methods your group considers as currently the most feasible will be appreciated. While you and other selected individuals are being contacted and the responses to this letter are evaluated, the University of Dayton will continue its study of methods. The responses to this letter will be used as a guide for a more detailed study and evaluation.

3. Although your participation is requested on a no cost basis, each individual responding will automatically receive a copy of the final report at no cost. Thank you for your interest and assistance. If there are any questions, please call me. (A/C 513, 229-2036)

Attach (2)

1 Summary of Methods (2)
2 Return Envelope

SUMMARY OF

IN SITU RAPID TESTING AND REMOTE SENSING METHODS RELATED TO AIRCRAFT FLOTATION AND OPERATING ON SOIL SURFACES

A. Rapid In Situ Test Methods (Related flotation, mobility, and trafficability of soil)				
METHOD (Add any method not listed)	PERSONAL RATING (Best=1, then 2, 3, etc.)	YOUR EXPERIENCE WITH METHOD		Please list references for other methods you have listed
		Good Points	Bad Points	
Mobility Cone - CI				
Aircraft Index - AI				
California Bearing Ratio - CBR				
Bevameter Shear				
Bevameter Bearing				

METHOD (Add any method not listed)	PERSONAL RATING (Best=1, then 2, 3, etc.)	YOUR EXPERIENCE WITH METHOD		Please list references for other methods you have listed
		Good Points	Bad Points	
Remolding Index				
Sheargraph				
Nuclear Methods (moisture, density)				
Dimensionless Analysis of Vehicle Rut Depth to Strength				

SUMMARY OF

IN SITU RAPID TESTING AND REMOTE SENSING METHODS RELATED TO AIRCRAFT FLOTATION AND OPERATING ON SOIL SURFACES

B. Remote Sensing Methods (related to flotation, mobility, and trafficability of soil)

METHOD (Add any method not listed)	PERSONAL RATING (Best=1, then 2, 3, etc.)	YOUR EXPERIENCE WITH METHOD		Please list references for other methods you have listed
		Good Points	Bad Points	
Airphoto Analysis				
Radar Mapping				
Laser Profilometer				
Multispectral Analysis				
Aerial Impact Penetrometer				

METHOD (Add any method not listed)	PERSONAL RATING (Best=1, then 2, 3, etc.)	YOUR EXPERIENCE WITH METHOD		Please list references for other methods you have listed
		Good Points	Bad Points	
Air Droppable Penetrometers				
Infared Mapping				
Microwave Radiometer				
Gamma Ray Analysis				

APPENDIX C

Descriptions of In Situ and Remote Evaluation Techniques

TEST METHOD: Penetration

TYPE: Mobility Cone - CI

Description: The mobility cone is a mechanical field instrument consisting of a 30° right circular cone with a 1/2 sq. in. base area mounted on one end of a 36 in. shaft. A proving ring with a dial gage and handle is mounted on top of the shaft. The dial gage reading is in terms of cone index, CI, given in psi to a maximum value of 300. CI numerically equals the force of penetration divided by the base area of the cone tip. The shaft is normally reduced to 3/8" diameter to avoid shaft friction. There is no presently available mathematical solution to the description of penetration resistance in terms of either soil stress-strain properties or classical failure theory parameters. The cone is sensitive to variations in its physical shape and size and speed of penetration, and thus the size and shape has been standardized as in the case of the mobility cone. The rate of penetration presently used as standard is 1.25 inches per second, and small deviations will not void the value obtained.

Procedure: Before starting the test, the dial indicator must be zeroed while the instrument is suspended by its handle. Then, placing the cone tip on the ground surface the operator positions himself to be able to force the cone into the ground while holding the device in a vertical plane. While penetrating the soil at a steady rate of approximately 1-1/4 inches per second, the operator reads the value of CI as the cone top enters the soil and takes subsequent readings at 3 inch intervals to a depth of 18 inches. The CI values are plotted versus depth and then the soil strength can be specified as the CI at a given depth of penetration or as an average CI over a given range of depth. Some care and experience are necessary to obtain good results and two men running the test help to make the data more reliable. It should be noted that this is an abbreviated version of the complete set of procedures and that the reference below should be consulted for details.

Discussion: For a CI value of 300, 150 pounds of force must be applied to the staff; therefore, an average man would find it difficult to use this instrument in hard soil (CBR 7.5) accurately. The device is for use in fine-grained soil and soil which contains large rock or which is composed mainly of large rock cannot be evaluated by this method. More than one CI test should be performed to establish the homogenity of the soil and to increase the reliability of the results, but the exact number of tests has to be determined in each case. This test is quick and easy to perform, and has been used in flotation research so that considerable correlation does exist for current flotation analysis. Over all, the mobility cone penetrometer is a good soil strength evaluation device, even though it does not measure a fundamental soil property but rather some combination of the fundamental strength parameters, cohesion and friction.

Reference: "Soils Trafficability", Department of the Army Technical Bulletin - TB ENG 37, Headquarters, Dept. of the Army, Washington 25, D.C., 10 July 1959.

TEST METHOD. Penetration

TYPE: Airfield Cone Penetrometer - AI

Description: The Airfield Cone is a field device that consists of a 30° right circular cone with a base diameter of 1/2 inch (area = 0.2 sq. in.), mounted on a graduated staff. On the opposite end of the staff are a spring, a load indicator, and a handle. The overall length of the assembled penetrometer is about 36 inches, and disassembled the longest piece is 14-3/4" long. There are two extension shafts, the handle, spring load assembly, two wrenches, and one extra cone tip in the airfield penetrometer package, and the total weight is about 2.6 pounds. The load is measured by a calibrated spring which is used in tension much like a spring scale, and the readings are given in tens of pounds. Thus, the maximum reading, which is 15, is equal to 150 lbs. on the device. The parameter measured is called the airfield index, AI, and is equal to the load on the tip divided by 10. Thus, AI is a measure of force. The only difference between AI and CI is the range of readings and the sensitivity of each instrument. CI equals fifty times the AI value.

Procedure: The procedure for operation of the airfield penetrometer is identical to that of the mobility cone penetrometer with the exception of the penetration rate, which is 1/2 to 1" per second for the airfield penetrometer. The readings are taken at specific depths as determined by the 2" graduations marked on the shaft to a maximum depth of 24". The device should be kept clean and oiled, and when performing a test care should be taken not to hit rocks while penetrating the soil. If a rock or other obstruction is hit during a test, the erroneous reading should be disregarded and a duplicate test run. Care should also be used when determining the depth of penetration for a given reading. This test is identical in form to that of the CI test and the data is redu[illegible] in the same fashion. The advantage of this device is related solely to the size of the tip, for in stronger soils it takes less load on the instrument to penetrate the soil.

Discussion: The weight of the operator as well as his strength limits the penetrometer reading and the device will not accurately measure soil properties in other than fine grained soils and sand. If possible, two men should run the test and many tests at a given site should be run to improve the reliability and accuracy. Some judgement must be exercised by the operator in evaluating the results, particularly if only a few tests are conducted. As with the mobility cone, the AI value is not a fundamental soil property, but rather some lumped strength parameter of cohesion and friction. Like the CI, the AI is a good indicator of strength for evaluating flotation capacity.

References: "Description and Application of Airfield Cone Penetrometer," W. B. Fenwick, Instruction Report No. 7, U.S. Army Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss., October 1965 (AD 600 746).

TEST METHOD: Penetration

TYPE: Remolding Index (RI)

Description: The remolding index is an expression designed to indicate the effect of multiple passes of a vehicle by describing the proportion of the original strength retained in a soil after that soil is remolded as measured by before and after CI readings. The equipment needed is the mobility cone penetrometer, a piston-type sampler that is 7 inches long and 1.9 inches in diameter, a base plate with attached cylinder of the same dimensions as the sampler, and a compaction drop hammer with a 12 inch free fall and weighing 2-1/2 pounds.

Procedure: A 6-inch sample which is obtained with the piston sampler is extruded into the cylinder and pushed to the bottom with the foot of the drop hammer compactor. The CI readings for this sample are taken as the the cone top enters the surface and at vertical increments of 1 inch to a depth of 4 inches. The sample is then remolded using 100 blows of the hammer, and the penetrations repeated. Dividing the average of the five CI values after remolding by the average of the five readings before remolding gives the RI value. The procedures used for obtaining the CI readings are similar to those used for the field test, except for the depths at which the CI value is read.

Discussion: This method is limited to fine grained soil and sand, and requires a considerable amount of equipment. There is the problem of reliability, for running 10 to 15 of these tests would be very time consuming and there are special procedures to be followed in some specific cases. Therefore, due to the reliability, equipment, and time limitations, the remolding index is not a good field evaluation tool for flotation analysis.

References: Department of the Army Technical Bulletin TB ENG 37, "Soils Trafficability", Headquarters, Dept. of the Army, Washington, D.C., 10 July 1959.

TEST METHOD: Penetration

TYPE: Airfield Penetrometer Remolding Index

Description: This index is identical to the remolding index, both in procedure and purpose, and is used when testing soils that exceed the range of values that can be measured by the mobility cone penetrometer. The equipment required to run this test is identical to the remolding index test with the exception of exchanging the airfield penetrometer for the mobility cone penetrometer.

Procedure: The procedures outlined for the remolding index are applicable to this test.

Discussion: As is the case with the remolding index, complex operational and analytical limitations make the airfield penetrometer remolding index impractical for an evaluation tool as related to flotation analysis.

Reference: Department of the Army Technical Bulletin TB ENG 37, "Soils Trafficability", Headquarters, Dept. of the Army, Washington 25, D. C., 10 July 1959.

TEST METHOD: Penetration

TYPE: Rating Cone Index - RCI

Description: The RCI is intended to express the soil strength rating of a point subjected to sustained traffic, and is numerically equal to the measured cone index multiplied by the remolding index. The equipment necessary to obtain a RCI value is the same as that for the remolding index.

Procedure: The remolding index, averaged over some area, is obtained in the standard fashion while CI values in situ are obtained at various specific locations. The RCI at those specific locations is the product of the average remolding index and the CI at that location as determined by standard CI procedures.

Discussion: The RCI is limited by large data collection and reduction requirements and by procedural complications, some of which are noted in the discussion of the CI and RI tests. Due to the above limitations, the RCI is not well suited for soil strength determinations for aircraft flotation analysis.

Reference: Department of the Army Technical Bulletin TB ENG 37, "Soils Trafficability", Headquarters, Dept. of the Army, Washington 25, D. C., 10 July 1959.

TEST METHOD: Nuclear

TYPE: Moisture and Density Determination by Backscatter and Direct Transmission Methods

Description: Nuclear instruments are commercially available devices that contain small nuclear sources for the purpose of emitting neutrons for moisture determinations and gamma rays for density determinations, by applying the principles of nuclear attenuation. The device contains a sensor or detector and a scaler that counts the neutrons or photons that return to the sensor by either backscatter or direct transmission. The density and moisture contents are functions of the transmission of these particles either through the medium or reflection off the medium. By use of a calibration curve, the readings can be converted to density or moisture content through the use of either direct count per minute or count ratio methods. These devices have been shown to be as accurate as the sand cone method and only take an approximate 15 minutes to get a moisture and density determination.

Procedure: The test surface must be level and free of loose material, and relatively free of large voids. The gauge is then placed on the soil surface and hooked up to the scaler. After allowance for warm-up time, three one-minute count readings are taken and the gauge is then rotated 90° or 180° and three more one-minute count readings are taken. The total of these six readings are divided by 6 times the standard count as determined during calibration. The wet density or water content can then be determined from the calibration curve. The latter description is the surface backscatter method using the count per minute calibration method. In the direct transmission method, the procedure is similar to the backscatter method, except that the probe is inserted into the ground before the readings are taken. In the air gap method, the gauge is set above the ground in a preset distance before the readings are taken, and the procedure is identical to the backscatter method for taking the readings.

Discussion: Nuclear devices measure very small quantities of soil in the determination of moisture and density. They measure to a depth of approximately 6 inches and for a volume of 0.1 cu. ft. of material maximum, depending on the material and the density. Calibration curves for each instrument should be determined to check the manufacturer's curve and verified each day. In addition, for accurate measurements, calibration curves need to be made for individual soils. The equipment, which is rather large and bulky, needs battery power or other power source and has many safety regulations that must be observed. The main drawback is the necessity of calibration for each soil type encountered and the reliability of the results. The principal advantage is the speed of operation and the non-destructiveness of the test.

References: "Evaluation of Nuclear Methods of Determining Surface in-Situ Soil Water Content and Density", T. B. Rosser, S. L. Webster, Misc. Paper S6915, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Miss., April 1969 (AD 688 079).

TEST METHOD: Penetration

TYPE: California Bearing Ratio (CBR)

Description: The CBR test is a plate bearing test to determine the CBR value which is the ratio of the load necessary to push a cylinder into the ground relative to a standard load. The apparatus is composed of a 3 sq. in. end area cylinder, a screw jack, surcharge weights, a proving ring, a dial gage, and some type of reaction frame.

Procedure: After setting up the CBR apparatus on a smooth soil surface, a test is run by forcing the piston into the soil at a rate of 0.05 inches per minute while recording the load at 0.025 inch intervals. After maximum penetration of 0.5 inches, the CBR value is calculated by dividing the measured load at 0.1 inch deflection by the standard load at 0.1 inch deflection. The standard load is obtained from a test on a typical well-graded crushed gravel. A standard annular surcharge weight of 10 pounds is normally placed on the surface before running the test, but if the test is not run at the original soil surface the surcharge weight is increased to approximate the weight of the overburden that was removed from the original surface. The load vs deflection curve is plotted to expose errors due to improper seating of the piston on the soil or premature shear failure. The standard values for load vs penetration for a typical well-graded crushed gravel are:

Penetration (in.)	Standard Load (psi)
0.1	1000
0.2	1500
0.3	1900
0.4	2300
0.5	2600

Discussion: This device is bulky and heavy, and requires a reaction frame for operation; therefore, it could not be carried by one man. There is considerable data compiled that relates CBR to flotation analysis and the CBR is a well known test that is generally understood by most engineers. The results, however, are not always consistent and the loading rate is low, but a major drawback is that the CBR measures strength only under a small deformation. Based on the above limitations and considering the length of time to run a CBR test, not to mention the experience required to interpret the results properly, the CBR test is not a good field evaluation device.

References: "Investigation of Test Bed for Airfield Matting Test Facility Model Soils and Boundary Effects", B. V. Washolder, Naval Air Engineering Lab (Ship Installation), Philadelphia, November 1954 (AD 820 420).

"Aircraft Landing Gear Dynamic Loads from Operation on Clay and Sandy Soil", C. K. Butterworth, W. B. Trusdale, AFFDL Air Force Systems Command, Wright-Patterson AFB, Ohio, March 1969 (Preliminary Data).

"Subgrade, Subbase, and Test Method for Pavement Base - Course Materials", Mil-Std-621A, 22 December, 1964.

TEST METHOD: Penetration

TYPE: Bevameter Bearing and Shear

Description: The bevameter bearing and shear apparatus are two entirely separate units, one of which is a measure of the shear strength of the soil and the other which measures the bearing capacity of the soil as related to trafficability. There are six different soil values obtained, three from the bearing unit and three from the shear device. The three parameters obtained from the bearing unit are identified as the moduli of sinkage, k_c and k_ϕ, and the exponent of sinkage, n. The parameters cohesion, c, angle of internal friction, ϕ, and the tangent modulus of deformation, K, are obtained from the shear test. These parameters are related to the bearing and shear tests through Bekker's load sinkage equation and a modified form of Coulomb's equation. The bevameter bearing equipment consists of a hydraulic load cylinder, a rotary potentiometer or helipot, a load cell or transducer, various sinkage footings, an X-Y plotter, and a reaction frame that is weighted by the operators standing on the frame. The shear device consists of a transmission, a shear head shaft, a shear head, a constant normal load applicator, instrumentation for measuring the normal load and torque, and a reaction frame similar to that of the bearing device. A power supply is necessary for both devices.

Procedure: Load Sinkage Test - The bearing device must be capable of developing 35 psi footing pressure, a load sinkage rate of 60 in/min., total travel of 18 inches, and at least 2% accuracy on the measurement of the load and deformation. The load-sinkage curve is continuously plotted during a test as the hydraulic cylinder is used to force the plate into the soil. The detailed procedures for obtaining one set of test values involves site preparation, trial tests and data reduction, and a minimum of six tests using three different plate sizes. The data reduction involves plotting the sinkage vs load data by plate sizes on logarithmic graph paper and drawing parallel straight lines through the data points of which the sinkages were two inches or greater. The slope of these lines define the value of "n" and the intercepts of these lines define constants that can be related to k_ϕ and k_c by a relation derived from Bekker's equation.

Shear Deformation Test - The shear device must be capable of rotating the shear head at approximately 10 rpm, free vertical motion of the shear head, maintain a constant load throughout the test, and have an annular shear head that has a minimum 5 inch inside radius. The shear stress-deformation data is recorded as the shear head is rotated under a given normal load to the point where the shear stress is a constant or until a constant rate of sinkage of the annulus occurs. The detailed procedure for obtaining one set of test values involves site preparation, equipment adjustment, and at least four different normal load readings with three repetitions each. The data reduction involves plotting the shear stress-deformation curve and then the ultimate shear stress vs normal load. The value of K is defined in terms of the initial portion of the shear stress-deformation curve, and the values of c and ϕ is determined from the ultimate shear stress vs normal load curve.

Discussion: It is obvious that these two devices are not well suited for rapid determination of soil strength because of the equipment size and power requirements alone. Other problems involving these tests include the sensitivity of the results to test procedure; seating of the shear annulus flush to the ground; erratic results obtained when roots, gravel, and rocks are present; and time involved in running sufficient tests to have reliable results. This test does attempt to measure fundamental soil properties yet the data reduction is not always possible and the results are questionable even with expert interpretation.

References: "Mobility Environmental Research Study Mobility Testing Procedures," R. A. Liston, et al., U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss., February 1966 (AD 800 462).

"A Study [illegible] Tropical Soil Strengths," D. A. Sloss and D. M. Lassaline, presented at the Second International Society for Terrain-Vehicle Systems, Quebec City, Canada, August 1966.

TEST METHOD: Shear

TYPE: Sheargraph

Description: The Soil Sheargraph is a small, hand-held self-recording field device that is designed to measure the angle of friction and the apparent cohesion of a soil. The device, which is 18 inches in length, is composed of a small grousered shear head with attached recording pen, a calibrated torsion spring, a recording drum with attached calibrated graph paper, and a handle.

Procedure: In operation, the shear head is completely inserted into the soil, normal stress is applied to the shear surface through axial deflection of the spring, and shearing stress is applied by twisting the recording drum until the soil fails. After soil shear failure occurs, the normal load is gradually reduced and, since the soil will sustain only a given amount of shearing stress for a particular normal load, the recording pen will trace the curve of shear stress versus normal stress as the latter is reduced to zero. The data recorded on the graph paper is reduced to values of cohesion and the friction angle by fairing a straight line through the average of all the test plots of shear stress versus normal stress. The slope of this line defines the angle of friction, and the intercept defines the value of apparent cohesion.

Discussion. The sheargraph was designed to measure only surface reaction of a soil for the purpose of evaluating surface traction of vehicles, and as such, does not adequately evaluate the action of a wheel unless the soil is particularly hard and cohesive. It will not adequately define the strength in cohesionless soil due to lack of strength at the surface, allowing sand to flow from beneath the device. Therefore, due to limited application and noting that there is no correlation between shear graph data and flotation analysis, the sheargraph is not a good method to evaluate soil strength for flotation analysis.

References: "Soil Sheargraph," G. T. Cohron, Agricultural Engineering: Vol. 44, No. 10, October 1963, pp. 554-556.

"Cohron Sheargraph for Shearing Strength Measurement," G. T. Cohron, Journal of Environmental Sciences: Vol. 6, No. 6, December 1963, pp. 17-20.

TEST METHOD: Penetration

TYPE: Military Vehicle Rut Depth Correlation

Description: The prediction of soil strength can be determined by relating experimentally the soil strength with the sinkage of a given military vehicle. There exists a relation of sinkage versus soil strength, tire size, weight, and other vehicle parameters, and therefore, through the use of dimensional analysis, a relationship that contains these variables can be determined and used to evaluate soil strength.

Procedures: To find the strength of a given field, a military truck of the type that has previously been calibrated by field tests is run over the soil surface. By measuring the soil deformation or rut depth, the soil strength can be determined by looking into a table for that type truck with some measure of its gross weight at the time to determine the strength of a soil corresponding to the amount of measured rut depth. This strength is then used as the strength of the soil, and can then be directly related to aircraft flotation performance.

Discussion: The feasibility of this method, which is rapid and easy to interpret, has been demonstrated in relation to heavier military vehicles. However, at the present time sufficient correlation has not been accomplished to fully evaluate soil strength based on military vehicle rut depth. Other than the weight of the military vehicle causing rut depths too small to measure, there are no limitations on this approximate method of predicting soil surface strength.

Reference: "Evaluation of Soil Strength of Unsurfaced Forward Airfields by Use of Ground Vehicles," G. M. Hammitt, Draft Copy, Report No. 1, Office Study, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, May 1968.

TEST METHOD: Remote Sensing Technique - Photography

TYPE: Metric and Multispectral

Description: Metric photography, which is a branch of the field of photo interpretation called photogrammetry, is a science which deals with measurement of objects as recorded on photographs. By use of stereo vertical photography, the photogrametrist can determine ground profiles and many other useful items such as soil type, moisture content, and degree of consolidation in crude form, but these latter items are arrived at only through extensive study by an expert photo interpreter. There are three general types of aerial photography: frame, panoramic; and strip type. At present, the frame type photography is better suited to the ascertaining of soil profile and roughness data, due to its stronger metric qualities; but the strip and panoramic types have much greater fidelity than the frame type, and therefore the metric qualities of strip and panoramic photography should be further developed.

Procedures: The frame camera is a conventional 9"x9" aerial mapping camera and is defined as a camera in which an entire frame or format is exposed through a lens that is fixed relative to the focal plane. The best type of camera for metric photography has a between-the-lens type shutter and uses roll film that is controlled automatically with the shutter. This type of camera, which can have a focal length range of 3-1/2 inches to 48 inches, can be equipped with image motion compensation which is necessary for metric work. The resolution in this type of photograph is variable, and is best at the principal point and gets worse as the radial distance increa es toward the edge. Common values of resolution are from 30 to 50 line pairs per mm.

Discussion: Some of the sources of error, when trying to interpret aerial photography, involve the density of the atmosphere at the time when the photography was exposed, radial and tangential lens distortion, film distortion, film thickness, migration of silver halide crystals during developing, emulsion creep, image irradiation, physical camera distortion, and actual size and shape of the silver halide crystals. Some of these errors, such as the density of the atmosphere, are not compensated and others, such as the radial and tangential lens distortion, involve physical impossibilities as compensation of the one causes errors in the other. Yet these errors are very small, and with state of the art techniques and equipment, most errors can be identified and compensated. It has to be remembered that the above discussion does not include the errors introduced by improper sun angle, haze in the atmosphere, ground coloring for contrast, height of the photography and scale, and many other small but important features.

Even considering the above mentioned problems, the Bendix report picks photography (i.e., the frame format type) as the best sensor for the site selection task for giving accurate profiles for cut and fill calculations and materials evaluation. This recommendation, based on the frame format's excellent metric quality, also stated that image motion compensation was essential and that convergent photography gives the best geometry for data analysis. Convergent photography, which is taken with two cameras tilted toward each other at some angle between 0° and 45°, gives better metric qualities than the standard type photography. It was also noted that strip and pan photography, which give excellent fidelity and resolution, may replace the frame format photography by improving the metric qualities of strip and pan through the use of analytical stereo plotting instead of manual plotting.

As an indication of the accuracy possible with aerial photography, the following equation is presented. This equation predicts the amount of error present in any one specific determination of the height of an object imaged in a photograph.

$$m_h = \frac{H^2}{B \cdot f} \cdot m_x^2$$

where, m_h = amount of error in a spot elevation determination

H = height of camera above terrain

B = difference in horizontal position between photographs

f = camera focal length

m_x = experimentally determined amount of error in any one reading and is the amount of parallax divided by 2 that can be resolved on the photograph. m_x changes for each photo and the best that can be gotten to date is 0.005 mm.

This equation assumes the use of an analytical stereoplotter such as the one developed by the Bendix Corporation, as well as perfect conditions for both photography and developing. The analytical plotter mentioned is very accurate and fast, but cannot now operate in a continuous mode at this accuracy level.

Actually, the essential part of using aerial photography data for flotation analysis is the developing of a correlation between the data presented on a photograph and flotation parameters so that the photo interpreter will have a correct interpretation key as has been done by WES. The reason for the need of this key is that the process of gathering information such as soil properties from photographs is one of inference. Therefore, to further aid in this process, the analysis of airphotos has taken many forms such as color, infrared, and multispectral photography. All of these assist in developing the basic flotation information and the analysis of these newer forms of photography is being done by computer through the use of spectral density measurements of the photos. The statistical analysis of such data show promise, but as yet have not yielded the answers to the basic problem of correlation from photo data to fundamental properties such as soil strength. Land forms, general classification of soil types, and identification of vegetation are all presently being done, but the best that can be expected for flotation analysis is an approximation of water content, density, and soil type. From just these three parameters a soil strength will have to be estimated, and, at present, such an estimate would be very crude.

Many specific examples of remote sensing accomplishments are available, yet there is not one completely usable system for the flotation analysis task. Therefore, the following examples of airphoto analysis will be presented in summary to indicate the state of the art.

The highly developed panchromatic photography, which is black and white photography, is the most widely used remote-sensing technique because of its availability, low cost, and high information content.

Infrared photography is sensitive to change in temperature, and, therefore, very accurately defines drainage patterns, bodies of water, some vegetation, and soil moisture contents.

Color photography is very useful in studying spectral signatures of soil types, vegetation, and other geologic features due to its many tonal characteristics, which become even more important in light of computer analysis of remote-sensor data.

Infrared color photography is another of the varied combinations that are possible for use as a remote sensing device. This type photography more clearly shows changes in vegetation and vegetation vigor than standard color photography.

Multispectral photography is an attempt to use the best features of all the spectral regions that can be recorded on film, and it requires accurate spectral signatures to be developed and computer data processing. It may be the best approach to remote-sensing of flotation data.

In the final analysis, aerial photography has been shown to be the most valuable and developed of all the remote sensors, yet the specific problem of relating airphoto data to flotation analysis has not been fully investigated at this time. Therefore, evaluation in definite terms cannot be made of airphoto analysis except to say that the evaluation of landing sites for aircraft does seem feasible from high quality photos on a non-real time basis. This would include a crude estimate of soil strength and some evaluation of surface roughness.

References: "An Optimum Multisensor Approach for Detailed Engineering Soil Mapping," H. T. Rib, Joint Highway Research Report Number 22, Purdue University, Lafayette, Indiana, December 1966 (PB 176310).

"Remote Sensing and its Application of Highway Engineering," HRB Special Report Number 102, Highway Research Board, Washington, D. C., December 1968.

"Airborne Remote-Sensing Techniques for Site Selection," Air Force Weapons Laboratory, Air Force Systems Command, AFWL TR 68115, December 1968 (AD 845 756).

Shamburger, J. H.; Mobility Environmental Research Study, A Quantitative Method for Describing Terrain Foreground Mobility: AD835392, U.S. Army WES, Corps of Engineers, Vicksburg, Mississippi, May, 1968.

TEST METHOD: Remote Sensing Technique - Infrared

TYPE: Scanners

Description: Infrared radiation, which is electromagnetic radiation in a band of wavelengths from about 0.7 to 1000 microns, is detected by a system which includes mirrors, reflectors, and some sort of infrared radiation detector. The mirror rotates and scans a path perpendicular to the flight path and the signal that the detector generates is turned into a light pulse which is recorded on film. The product is a map of the terrain that is dependent on the thermal emissivity properties of the surface scanned. Texas Instrument has developed an aerial infrared mapping system, the RS-7 model, which uses a mercury-doped germanium detector and records on 70 mm film in the 8 to 14 micron region. It is interesting to note that below 3.5 microns, the sensor is seeing mainly reflected sunlight, and that above 3.5 microns it sees mainly emitted energy.

Discussion: The thermal emissivity of a soil surface, which can be correlated to the moisture content and the soil texture in some cases, can detect drainage patterns and vegetation rather easily, primarily because the moisture content of materials exerts the major control on the thermal emissivity. The tone of the thermal map is the key to these correlations, but the problem is that the tone is dependent upon:

1. Terrain radiant emittance characteristics
2. Geometric relationship between the terrain and the sensor system
3. Environmental modification such as wind, humidity, and temperature
4. System settings
5. Image processing and reproduction.

All of the above items have to be taken into account accurately and corrections applied to the results before meaningful data can be determined, thus making extensive correlation of emissivity characteristics to the problem of soil moisture and texture, which still need to be done, very difficult.

In a recent study the infrared imagery from predawn flights was shown to be the best data for correlation purposes, and it was further shown that some of the soils could be delineated by high, medium, and low water contents. Organic soils were also detectable, as was near surface rock and the infrared imagery proved to be an excellent tracking device for the laser profiler.

Direct recording of the temperature can be collected and used to compile isothermal contour maps which will help to delineate soil textural and moisture characteristics, surface water, and surface and near-surface rock. Very small differences in temperature (2° to 4° absolute) can be detected by these systems. Thus, if a correlation between soil properties and temperature can be determined, the infrared radiometric data can predict some of these soil properties. Note that for use of this method, good weather is required and the infrared radiation must be gathered in one of two limited regions of the electromagnetic spectrum (2 to 5 and 7 to 14 micron regions) that does not seriously attenuate the emittance from the surface.

Infrared imagery, for example, would seem to be able to indicate the homogenity of the surface very well, and this is an important consideration for the landing gear problem. It is important to note that infrared imagery alone cannot be used to any great advantage for flotation analysis purposes, but that when used in conjunction with other sensors can highlight variations in soil texture, composition, and moisture content. It is very helpful in soil mapping, outlining rock formations, and exposing hidden subsurface conditions. One interesting application is the plotting of ground water movement from underground sources to some water body.

The infrared radiometer is another type of infrared scanning device that records the surface temperature directly on a strip chart recorder. These devices have less data reduction requirements and are easier to use. They are good for periodic measurements of thermal radiation, where a study of the change of thermal emissivity with time is of interest.

References: "Air Optimum Multisensor Approach for Detailed Engineering Soils Mapping," H. T. Rib, Joint Highway Research Project, Report No. 22, Purdue University, Lafayette, Indiana, December 1966 (PB 176310).

"Airborne Remote-Sensing Techniques for Site Selection," F. J. Buckmeier, et al., AFWL TR-68115, Air Force Weapons L oratory, Air Force Systems Command, Kirtland Air Force Base, N. Mex., December 1968 (AD 845 756)

Letter of communcation with Air Force Weapons Lab, Kirtland Air Force Base, New Mexico.

"Remote Sensing and Its Application to Highway Engineering," Highway Research Board Special Report 102, Highway Research Board, Washington, D. C., December 1968.

TEST METHOD: Remote Sensing Technique - Radar

TYPE: Side-Looking Radar

Description: Imaging radar, which uses the region of the electromagnetic spectrum between 1 mm and 1 meter, is essentially a simple electric circuit consisting of an energy source, a transmission medium, and an energy receiver, and the basic principles of the side-looking radar are the same as those of a simple ranging radar. Short pulses of energy are sent out from the transmitter, and the energy that is reflected off the object or surface is received by an antenna and recorded. The time duration between the pulse, the so-called "echo", is a measure of the range of the surface or object and the amount of the energy returned is a measure of the reflectivity of the object.

The signal that is returned to the antenna is displayed on a cathode ray tube (CRT) as a single line. The sweep of the electron beam is begun upon return of the signal and the traced line is modulated by the return signal which causes a presentation of the reflectivity of ground objects along a narrow path normal to the flight line. The display is recorded on moving film line by line and by continuous scanning forms a type of map, although the image picture defined by this map is very dissimilar from photographs.

The sensitivity and range resolution of a given system is dependent upon pulse duration and antenna characteristics, such that longer antennae refine data and a shorter pulse gives better resolution. Modulation techniques help to obtain the shorter pulses for increased resolution, and electronic data storage and processing techniques will also increase resolution.

Discussion: The greatest advantage of this type sensor is that the radar can penetrate the atmosphere even in poor weather conditions and its ability to penetrate is a function of the frequency such that, generally, the lower the frequency the greater the penetration ability. However, radar cannot penetrate heavy rain storms due to signal return from the rain.

This method of sensing terrain data has not, unfortunately, been shown to be a feasible method at this time for soil strength and roughness determinations. The SLR records are being used to identify military targets, gross topographical data, and major environmental targets. It is being researched for extension to geological data and possible engineering type data in that longer wave lengths radars can penetrate the soil to great depths. The major problems with this sensor are the lack of knowledge of the actual relationships between the reflectivity and the materials reflected, and the complex relationships governing the interpretation of the records due to sensor-surface orientation. The radar pulses sent out, for example, penetrate some soils and not others causing different return signals, but work has been, and is being, done on the physical relationships between the reflectivity and the soil properties. Radar records have been shown to be an indicator of some physical properties of soil. Radar sensors can provide information on moisture content in deep homogeneous soils although they cannot predict the depth of surface water, presence of ground water, or depth to ground water. Radar does provide a fairly accurate medium for interpretation of geology and lithology in mountainous regions and can be useful for compilation of vegetation maps, materials maps, and regional reconnaissance services.

Again, as is pointed out with the other sensors, this device needs additional research and study before the feasibility of using SLR for determination of soil strength and roughness parameters can be shown. The SLR will be best used as one part in a complex reconnaissance system where other sensors help with the interpretation of the SLR.

References: "An Optimum Multisensor Approach for Detailed Engineering Soils Mapping," H. T. Rib, Joint Highway Research Project C-36-32U, Purdue University, Lafayette, Indiana, December 1966 (PB 176310).

"Site Selection Techniques," R. E. Forrest, Bendix Corp., Southfield Michigan, Bendix Research Labs RLD 4288, AFWL TR-67-146, May 1968 (AD 835 230).

"Airborne Remote-Sensing Techniques for Site Selection," F. J. Buckmeier, et al., AFWL TR-68115, Air Force Weapons Laboratory, Air Force Systems Command, Kirtland Air Force Base, N. Mex., December 1968 (AD 845 756).

TEST METHOD: Remote Sensing Technique - Profile Recorders

TYPE: Laser

Description: The laser profiler, which is a system composed of a modulated continuous wave (CW) gas laser, a barometric altimeter, and a photographic recording system, operates as a simple ranging system using a transmitted laser beam that is picked up by a photomultiplier detector upon return from some surface. The aircraft flies over a field at a relatively constant speed and altitude as the laser measures the height of the aircraft above the terrain and the barometric altimeter records the elevation of the aircraft. The profile is plotted from this data for the path shown by the photos taken with the laser data.

Discussion: The system just described is very unsophisticated, and since its conception the laser profiler has undergone a great deal of development. The lasers are now more powerful and the systems more precise than the type described above.

The major system error is determined through signal to noise considerations, which are common to devices that use photomultiplier tubes. Aero-Services and Spectra-Physics wrote an internal report that describes the theoretical analysis of such a system. Their analysis and testing in 1965 showed that elevation differences of ±1 foot are obtainable and they indicated that the profile can be determined if the beam hits the soil surface only 5% of the time (i.e., in a forest).

WES tested a CW gas laser that was modulated at three different possible frequencies and this study showed that the laser profiler still had problems with system noise and aircraft roll and pitch stabilization. The laser profiles only what it sees, thus, when profiling over grass the results showed the mean grass height and not the surface. Again, the reference system for altitude needs work, but WES concluded that vertical elevations to ±0.3 feet are obtainable.

Texas Instruments also have reported on the use of the laser profilers, using the Spectra-Physics equipment. Their results indicate the profiler can measure to ±1 ft. accurately and could possibly measure to 0.2 ft. with a more sophisticated system. The error associated with altitude and attitude of the aircraft are all again noted as a major source of error. The results also showed that signal drop-out limited the laser profiles to a 2500 ft. altitude above the ground and that weather conditions such as intervening clouds, fog, smoke, or precipitation severely attenuated the signal and produced unreliable information. WES recommends that the output of the laser profiler be digitized to supply a well defined time and spatial base for the data.

Some of the problems mentioned above can be overcome with improvement in technology, but cost is certainly an obstacle and has been a limitation in all previous systems. Overall, the laser profiler appears to be a very promising device for the remote sensing of ground roughness.

References: "An Information Note on an Airborne Laser Terrain Profiler and Micro-Relief Studies," R. Demple and A. K. Parker, Proc. Third Symposium Remote Sensing, University of Michigan, Ann Arbor, Michigan, 1964.

"Capacity of Airborne Laser Profilometer to Measure Terrain Roughness," L. E. Mink, Proc. Sixth Symposium Remote Sensing, University of Michigan, Ann Arbor, Michigan, 1969.

Communication with Air Force Weapons Laboratory, Kirtland Air Force Base, N. Mex.

TEST METHOD: Remote Sensing Technique - Impact Penetrometers

TYPE: Aerial Cone and others

Description: The original impact penetrometer, which was the U.S. Air Force aerial cone penetrometer, was designed to indicate only one level of soil strength, thereby evaluating the soil for aircraft flotation on a go, no go basis. The aerial cone device is composed of a slender tubular body which holds a shear-pin firing device and a flare, a cone tip, and tail fins for stabilization. The level of soil strength indicated by this device depends on the size shear-pin that has been installed, for when the aerial cone impacts the soil surface the flare is either set off by the impact or the soil strength is below that value which will cause failure of the shear pin. The basic idea behind the aerial cone is very good and the device worked when considered within its limitations which included the necessity of dropping many devices to have a reliable evaluation of soil strength.

More recently, the aerial penetrometer approach has been converted to an impact penetrometer that measures the time vs. deceleration curve of an impact object on the soil surface. The most advanced types of impact penetrometers are spheres that have three mutually perpendicular accelerometers, thus giving time vs. deceleration curves which are independent of impact geometry.

Discussion: As with all methods of experimental testing, especially in soil mechanics, the most important consideration is the analysis of the data, and here again the analysis of the impact penetrometer does not, at this time, reveal any fundamental soil property. The analysis of the impact penetrometer as developed by Princeton University has used a Maxwell model to represent the impact loads and they have been able to distinguish different soil responses using this method in a limited number of cases. This is not a fundamental solution to the problem of aircraft tire-soil interaction, but does seem to be a feasible method of evaluating soil strength on a semiempirical basis. This approach is, in fact, the only method available to directly measure soil strength by remote means.

References: "Remote Determination of Soil Trafficability by the Aerial Penetrometer," by C. E. Molineux, AFCRC-55-223, Air Force Cambridge Research Center, Bedford, Mass., October 1955 (AD92254).

"Strength Response Parameters of Natural Soil Surfaces and Their Application to the Landing Program of Aircraft," by Kuei-wu Tsai, AFCRL 67-0583, Princeton University, Princeton, N. J., January 1967.

TEST METHOD: Remote Sensing Technique - Microwave

TYPE: Radiometry and Imagery

Description: Microwave sensors, which detect radiation in the region of the electromagnetic spectrum between 1 mm and 1 meter, are similar to both radar and infrared devices in that the instrumentation is usually that of radar and the radiation sensed is both passive and temperature sensitive, as is infrared radiation. This radiation can be recorded either as apparent temperatures at selected frequencies, which is done with the radiometer, or can be recorded as a temperature map or imagery. The radiation energy emitted from soil is a function of both emitted and reflected energy and the equipment, usually radar, receiving this energy is controlled by factors including bandwidth, antenna characteristics, and receiver characteristics.

Discussion: Microwave sensors are the least developed of the new remote sensing devices, yet there are many useful applications for microwave devices, especially for bad weather operations. Some of the problems with interpreting microwave data involve frequency of sensing, the relative dielectric constant of the soil, the surface roughness, the angle of incidence, plus all the normal parameters that complicate interpretation of all types of sensor data. These complicating factors include the weather, seasonal changes, contrast with surroundings, and many others.

The microwave sensor gives approximately the same resolution as a comparable infrared sensor, yet the microwave sensor has the ability to sense data, as related to temperature, that is dependent upon soil properties other than at the soil surface. Therefore, like active radar devices, the microwave sensor applications will involve studies concerning soil layering, moisture content with depth, and other subsurface types of phenomena.

References: "An Optimum Multisensor Approach for Detailed Engineering Soils Mapping," by H. T. Rib, Joint Highway Research Project No. 22, Purdue University, Lafayette, Indiana, December 1966 (PB 176310).

"Airborne Remote-Sensing Techniques for Site Selection," F. J. Buckmeier, et al., AFWL TR-68115, Air Force Weapons Laboratory, Air Force Systems Command, Kirtland Air Force Base, N. Mex., December 1968 (AD 845 756).

TEST METHOD: Remote Sensing Technique - Gamma Ray

TYPE: Spectrometer

Description: This relatively new sensor technique measures levels of natural radioactive emission of various materials in the gamma ray region of the electromagnetic spectrum. The levels of emittance of radiation, which comes mainly from concentrations of uranium, thorium, and potassium, have been shown to be unique in some soils as related to soil type.

Discussion: Some of the problems associated with the gamma ray-type of sensor involve an altitude limitation of 500 feet, daylight operation, good weather, and a surface area free of water and snow. The ability to sense gamma radiation is extremely sensitive to these parameters and, as with the other sensors described in this report, there are many operational and data reduction problems associated with such parameters as seasonal changes, wind factors, time of day, and many others.

References: "Airborne Remote-Sensing Techniques for Site Selection," F. J. Buckmeier, et al., AFWL TR-68115, Air Force Weapons Laboratory, Air Force Systems Command, Kirtland Air Force Base, N. Mex., December 1968 (AD 845 756).

TEST METHOD: Remote Sensing Technique - Multisensor

TYPE:

Description: A multisensor approach to remote sensing, which combines many different remote sensing devices using both multispectral and multiband combinations, is designed to use the best combination of remote sensors for some specific task. Therefore, the determination of which sensors are capable of measuring pertinent engineering terrain parameters must be accomplished before a multisensor system can be designed. The ideal system is one which obtains simultaneous coverage of the test area with the various sensors, at the same time, the same detail, and the same format in order to facilitate both comparison of the different imagery and handling of data and measurements.

Discussion: There are presently many widely varied multisensor systems being studied, but these systems are still being evaluated as to their applications to specific problems. The limitations of the multisensor approach are yet unknown, and the factors to be considered in designing such a system include: purpose, economics, time, personnel, equipment availability, techniques of handling and interpretation of data, and data compatibility, to mention only a few. Based on the limited knowledge of remote sensor systems, and the possibilities revealed by the multisensor approach, it seems that this method provides the ultimate in data gathering and may possibly be the key to the proper interpretation of all remote sensing data.

Reference: "An Optimum Multisensor Approach for Detailed Engineering Soils Mapping," H. T. Rib, Joint Highway Research Project Report No. 22, Purdue University, Lafayette, Indiana, December 1966 (PB 176310).

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) University of Dayton Research Institute, 300 College Park, Dayton, Ohio 45409	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

Aircraft Surface Operation - Soil Surface Correlation Study

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report, 15 August 1969 to 15 February 1970

5. AUTHOR(S) (First name, middle initial, last name)

Kraft, David C.
Hoppenjans, J. Richard

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1970	94	34

8a. CONTRACT OR GRANT NO. AF 33615-70-C-1019 b. PROJECT NO. 1369 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) AFFDL-TR-70-30 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None

10. DISTRIBUTION STATEMENT This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics (FDFM), Wright-Patterson AFB, Ohio 45433.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Vehicle Equipment Division, A. F. Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

Ultimate goals of Air Force landing gear/soil interaction research are to develop maximized landing gear design criteria for aircraft operation on soil surfaces and to establish absolute techniques for the prediction of military aircraft operational capability at any soil surfaced site. In order to achieve these goals, real life relationships must be established between aircraft surface operational capability, and soil and site characteristics.

This program was concerned with the identification of both soil and site parameters usable for defining aircraft operations capability. The research effort included a literature survey, a review of existing rapid in situ and remote sensing techniques for determining soil strength and ground roughness, and a study of the proposed active landing gear system as related to the required soil and site parameters. A detailed description of each of the reviewed rapid in situ and remote sensing techniques is included.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

Security Classification

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
In Situ Soil Testing						
Remote Sensors						
Soil Parameters						
Roughness						
Active Landing Gear						
Flotation						

UNCLASSIFIED

Security Classification